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A Study of DRAINMOD-Urban For Enhanced Bioretention Cell Modeling

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To the Graduate Council:

I am submitting herewith a dissertation written by Whitney A. Lisenbee entitled "A Study of DRAINMOD-Urban For Enhanced Bioretention Cell Modeling." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Environmental Engineering.

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A Study of DRAINMOD-Urban for Enhanced Bioretention Cell Modeling

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Whitney A. Lisenbee

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DEDICATION

This dissertation is dedicated to my mom.
Watching you realize your dream of attaining a PhD made this goal seem more achievable to me.
Thank you for showing me what hard work and dedication can accomplish.

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ABSTRACT

Bioretention has become a leading infiltration-based stormwater control measure for mitigating urban hydrology by reducing urban stormwater runoff volumes and peak flows. Despite widespread field and laboratory studies, less investigation has been directed toward effectively modeling these systems. This is critical, as modeling of bioretention systems provides an avenue for evaluating their effectiveness prior to devoting time and resources into installation. Many hydrologic models capable of simulating bioretention consist of lumped parameters and simplifications that do not fully account for fundamental hydrologic processes such as soil-water interactions. One model, DRAINMOD, has overcome many limitations of other models by incorporating the soil-water characteristic curve (SWCC) to provide better analysis of soil moisture conditions within a bioretention cell and offering better drainage configurations such as an internal water storage (IWS) zone. DRAINMOD is an agricultural drainage model that has shown promise when applied to bioretention systems but operates at a daily temporal scale which does not capture rapid changes in urban hydrology. This study begins by modifying DRAINMOD to adapt to the flashy nature of urban hydrology and bioretention systems in a new model named DRAINMOD-Urban. The performance of DRAINMOD-Urban established that it can produce output hydrographs that represent measured drainage and overflow from a bioretention system while still maintaining calibrated volumes of outflow similar to DRAINMOD. Next, DRAINMOD-Urban was compared to the LID module of the commonly used hydrologic model, the U.S. Environmental Protection Agency (EPA) Stormwater Management Model (SWMM). DRAINMOD-Urban produced better drainage hydrographs but SWMM was very accurate at predicting measured drainage (NSE=0.77-0.94) and overflow (NSE=0.67-0.81) volumes. Pedotransfer functions (PTF) were used to derive the SWCC and

saturated hydraulic conductivity required for DRAINMOD-Urban and model performance was compared among measured and PTF-derived soil properties. This study showed that a calibrated DRAINMOD-Urban can perform equally well with a SWCC that is measured and calculated using the ROSETTA PTF. These investigations provide a better understanding of how DRAINMOD-Urban has enhanced the field of bioretention cell modeling at the site-scale.

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INTRODUCTION

Background on Bioretention

Increased urbanization and its associated increase in impervious surfaces have dramatically altered the hydrology of landscapes leading to increased stormwater runoff. This, in turn, has intensified other environmental problems such as stream channelization, increased flooding downstream, decreased water quality from sediment and nutrients, and heavy metals carried by stormwater, and declining aquatic habitats (Dietrich et al., 2017; Liu et al., 2014a; Asleson et al., 2009). According to the most recent National Water Quality Inventory, 55% of assessed streams throughout the United States are listed as impaired with urban stormwater runoff as one of the leading causes of water quality impairment (U.S. EPA, 2017).

To combat these problems, new methods of approaching stormwater management have been developed to reduce the volume and peak flows of urban runoff by increasing infiltration and evapotranspiration (ET). This concept, referred to as Low Impact Development (LID), is an urban-planning technique that focuses on reducing the effects of urbanization. Typical examples of LID practices include permeable pavement, green roofs and rain barrels with the most prevalent being bioretention cells (Kaykhosravi et al., 2018; Dietrich et al., 2017; Liu et al., 2014a; Davis et al., 2009). Bioretention is the predominant choice of LID in many areas because it can control the volume, rate, and quality of stormwater runoff (Akan, 2013).

A typical bioretention system is a small vegetated depression that creates a ponding zone for storage before filtering through layers of highly infiltrative soil: bioretention media, sand, and subsequently gravel. Often, to meet drawdown requirements (typically 24-48 hours), a perforated underdrain is placed in the gravel layer to improve drainage instead of relying on exfiltration into the surrounding soil (National Research Council, 2009; Ohio Department of Natural Resources, 2006). Bioretention systems have been widely accepted among municipalities and within the engineering community due to many field studies demonstrating impressive runoff volume reductions (Olszewski and Davis, 2013; Davis et al., 2012; Li and Davis, 2009; Hunt et al., 2006) and water quality improvement (Brown and Hunt, 2011b; Chapman and Horner, 2010; Passeport et al., 2009; Davis et al., 2006).

Many studies have been conducted on field sites to assess performance of bioretention cells with varying design attributes (Al-Ameri et al., 2018; Wan et al., 2018; Jiang et al., 2017; Lopez et al., 2016; Lucke and Nichols, 2015; Paus et al., 2014; Brown et al., 2013a; Komlos and Traver, 2012; Brown and Hunt, 2011a; 2010; Li et al., 2009; Line and Hunt, 2009; Davis, 2008; Hunt et al., 2006; Hsieh and Davis, 2005). Even mesocosm or column studies have received widespread attention in bioretention research (Wang et al., 2018; Goh et al., 2017; Liu and Fassman-Beck, 2017; Ray et al., 2015; Wadzuk et al., 2015; Liu et al., 2014b; Payne et al., 2014; Palmer et al., 2013; Good et al., 2012; Lucas and Greenway, 2011b; 2011a; 2011c; Stander and Borst, 2010; Li and Davis, 2008a; Lucas and Greenway, 2008; Hsieh et al., 2007b; 2007a). Comparatively, bioretention cell modeling has received less attention but a review of models used for bioretention is provided in Chapter 1.

Bioretention Modeling

Computational models have been slow to develop for bioretention systems despite the importance of being able to test these systems prior to investment of time, money, and resources. Modeling of bioretention allows designers to better optimize bioretention cell design and performance, provide guidance for design standards, and scale local impacts to the larger watershed. There are many hydrologic models that have developed tools for modeling bioretention. However, existing models applied to bioretention use simplifications that do not fully account for fundamental hydrologic processes. Developing widely-available, effective models for bioretention systems could lead to increased adoption of these systems (Elliott and Trowsdale, 2007).

Many early bioretention models lacked long-term, continuous simulation which ignored the effect of antecedent moisture conditions in the soil, an important consideration that affects the infiltration capabilities of the system (Elliott and Trowsdale, 2007; Heasom et al., 2006). Further, many models use infiltration processes that assume uniform saturation of the media, while field measurements confirm bioretention systems are variably saturated and unsaturated during and following rain events (Brown et al., 2013b). As an example of the importance of these assumptions, in the mathematical bioretention model developed by Guo and Luu (2015), the hydraulic conductivity and initial soil moisture were named primary calibration parameters emphasizing the significance of soil-moisture accounting in bioretention modeling.

Another limitation of current bioretention models is that many have insufficient capabilities for modeling flow to underdrains despite this being a common design feature. Often underdrains are represented as a single pipe in the gravel layer such as in RECARGA and SWMM. These models limit the configuration of the underdrain such that the common upturned elbow design used for an internal water storage (IWS) zone is difficult to model accurately (Liu and Fassman-Beck, 2017; Brown et al., 2013b). Improving drainage configurations to include other outlet structures and flow restrictions such as valves, orifice plates, weirs, etc. would greatly increase the field installations that can be represented in the model.

Many studies model bioretention cells at a catchment scale and are primarily concerned with the total runoff reduction these devices provide to the catchment. However, to understand the change in flow behavior throughout a catchment, the outflow hydrographs from each bioretention cell must be examined. Few studies have calibrated flow from the underdrain in bioretention models to measured drainage and those that have are primarily mesocosm or column studies (Gulbaz and Kazezyilmaz-Alhan, 2017; Liu and Fassman-Beck, 2017; Massoudieh et al., 2017; Li and Lam, 2015; Meng et al., 2014). There is a need for more field calibration of model performance for flow through underdrains to ascertain how the flow dynamics through the bioretention cell is modeled.

One of the most common models used for bioretention applications is the United States Environmental Protection Agency (EPA) Storm Water Management Model (SWMM). SWMM is a well-known hydrologic model that includes an "LID module" to model bioretention cells and other sustainable stormwater systems (Rossman, 2010). A benefit of using SWMM is that it can model bioretention cells across a watershed (Avellaneda et al., 2017; Dietrich et al., 2017; Palla and Gnecco, 2015; Rosa et al., 2015; Bosley, 2008). Other bioretention models include common hydrologic models such as HEC-HMS and HydroCAD (Lucas, 2010; Heasom et al., 2006). In these studies, popular hydrologic models were retrofitted to resemble the hydrology of a bioretention cell, but these models do not provide explicit functions for bioretention modeling.

DRAINMOD

DRAINMOD is an agricultural drainage model that has shown promise when applied to bioretention systems (Winston, 2015; Hathaway et al., 2014; Brown et al., 2013b). It has the capability of using the soil-water characteristic curve (SWCC) to obtain detailed water balances over a continuous, long-term time-period. This detailed soil-moisture accounting is an improvement over other models for bioretention that assume field capacity or saturation. For instance, Brown et al. (2013b) showed that calculating the total volume drained using the SWCC compared to assuming a moisture content of saturation minus field capacity created very large errors (-6017 to -14% different), especially with high internal water levels. Therefore, the SWCC is a better parameter to use in determining infiltration through bioretention systems since the water level is often near the surface or held within the cell in an IWS zone.

Brown et al. (2013b) and Brown (2011) were the first studies to investigate using DRAINMOD to model the hydrology of bioretention cells. These studies monitored four bioretention cells in North Carolina and modeled them using DRAINMOD to obtain volumes from each fraction of the water balance (inflow, infiltration, drainage, exfiltration, evapotranspiration, and overflow). Calibration and validation of the model show good agreement with measured values with Nash-Sutcliffe coefficients ranging from 0.6-0.9 for drainage, outflow and exfiltration of all the bioretention cells studied. This study proved that DRAINMOD, with its ability to model IWS zones and its improved soil-moisture accounting, can accurately model the water balance of a bioretention cell.

Winston (2015) utilized the knowledge brought forth by Brown et al., to test DRAINMOD on three more bioretention cells in Ohio. This study focused on modeling bioretention cells with an IWS zone and those built on poorly draining, HSG D, soils. All three bioretention cells in this study also demonstrated good model agreement with measured values and the Nash-Sutcliffe coefficients ranged from 0.94-0.99 for the calibration period and 0.73-0.99 for the validation period.

These studies establish that DRAINMOD is well-suited for modeling bioretention cells, especially given its improved infiltration and drainage capabilities over other models. However, DRAINMOD was designed for agricultural purposes and aggregates volumes of flow within the bioretention cell at a daily time step. Therefore, due to the rapid response times in urban systems, it cannot produce hydrographs of hydrologic flow paths in the bioretention cell. For this study, DRAINMOD has been recoded to create DRAINMOD-Urban. This updated model allows for high temporal resolution inputs and outputs, more closely matching the travel times of urban systems. More information on DRAINMOD-Urban and its modifications can be found below.

DRAINMOD modifications

As previously noted, DRAINMOD was re-coded to better represent the rapid response time of an urban runoff hydrograph. DRAINMOD originally accepted hourly precipitation inputs as the finest time-scale available. In addition to concerns over the temporal resolution of the model, the original model also provided a "Contributing Area Runoff" function but did not allow for input of measured runoff entering the bioretention system from the drainage area. DRAINMOD-Urban was created to allow 1-minute precipitation inputs and 1-minute runoff/inflow from the drainage area. The outputs [infiltration, drainage (outflow), runoff (overflow), ET, and seepage (exfiltration)] are also at 1-minute intervals. These output terms represent the terminology used by DRAINMOD while those in parentheses are terms common to the bioretention field. For the remainder of this paper, the term drainage refers to flow through the underdrain and overflow will refer to surface runoff leaving the ponding zone of the bioretention cell. The improved DRAINMOD-Urban outputs can be used to examine the hydrograph and peak flow of each water balance component, which was not possible in the previous version of the model. As these changes to DRAINMOD were tested on the bioretention cell mentioned in this paper, model behavior was inspected and appropriate adjustments were executed in the model programming. Because of the emphasis on DRAINMOD-Urban in this dissertation, details regarding model calculations and input parameters are given in the next section.

DRAINMOD Governing Equations

DRAINMOD is a process-based, distributed model that produces water balances of agricultural drainage plots at a field-scale on hourly or daily time steps. The outputs of the model are summarized on a daily, monthly, yearly and ranked bases. A water balance is computed first at the soil surface such that:

$$P = F + \Delta S + RO \tag{4}$$

where P is the precipitation (cm), F is infiltration (cm), ΔS is the change in surface storage at the surface (cm), and RO is the runoff (cm). When the surface storage is full, ΔS is zero and the resulting surface runoff can be calculated as $RO = P - F$.

Another water balance is computed in the soil section from the surface to the impermeable layer as the average water table depth midway between soil drains, expressed as:

$$\Delta V_a = D + ET + DLS - F \tag{3}$$

where ΔV_a is the change in water-free pore space or air volume (cm), D is drainage from the section (cm), ET is evapotranspiration (cm), DLS is deep and lateral seepage (cm), and F is infiltration entering the section (cm).

To calculate infiltration, DRAINMOD uses the Green and Ampt (1911) equation:

$$f = K + KM_d S_f / F \tag{5}$$

where f is the infiltration rate (cm/hr), F is the cumulative infiltration (cm), K is the vertical hydraulic conductivity (cm/hr), M_d is the change in volumetric water content (cm^3/cm^3) and S_f is the effective suction at the wetting front (cm). This equation can be simplified for a single soil with a given initial moisture content to be expressed as:

$$f = \frac{A}{F} + B \tag{6}$$

where *A* and *B* are termed the Green-Ampt parameters and are derived from the SWCC at varying water table depths using the built-in the soil preperation program in DRAINMOD which is discussed further below. Soil properties can be used to approximate the infiltration parameters when these parameters cannot be identified through regression fitting of measured infiltration data.

The subsurface drainage represents the outflow from the underdrain in a bioretention cell. When the soil profile is saturated and water is ponded on the surface, the D-F assumption no longer apply so the Kirkham equation (1957) is applied in DRAINMOD:

$$q = 4\pi K(t + d - r)/GL \tag{7}$$

where *K* = effective lateral saturated hydraulic conductivity, *t* = ponding depth, *d*= drain depth, *r*=drain radius, *L*= drain spacing, and G= Kirkham's coefficient. G is defined as:

$$G = 2\ln\left[\frac{\tan\left(\frac{\pi(2d-r)}{4h}\right)}{\tan\left(\frac{\pi r}{4h}\right)}\right] + 2\sum_{m=1}^{\infty} \ln\left[\frac{\cosh\left(\frac{\pi mL}{2h}\right)+\cos\left(\frac{\pi r}{2h}\right)}{\cosh\left(\frac{\pi mL}{2h}\right)-\cos\left(\frac{\pi r}{2h}\right)} \cdot \frac{\cosh\left(\frac{\pi mL}{2h}\right)-\cos\left(\frac{\pi(2d-r)}{2h}\right)}{\cosh\left(\frac{\pi mL}{2h}\right)+\cos\left(\frac{\pi(2d-r)}{2h}\right)}\right] \tag{8}$$

where *d*= drain depth, *r*=drain radius, *h*= the depth of the profile, *m* = water table height above the drains at the midpoint, and *L* = drain spacing.

As drainage and evaporation continues, the water level starts to develop an approximately elliptical shape and the soil profile becomes unsaturated. Under these conditions, Kirkham's equation is no longer valid and radial flow near the drains is calculated using the steady state Hooghoudt equation (van Schilfgaarde, 1974) :

$$q = 8Kd_e m + 4Km^2/L^2 \tag{9}$$

where *q*= subsurface drainage rate, *K* = effective lateral saturated hydraulic conductivity, d_e = equivalent drain depth, *m* = water table height above the drains at the midpoint, and *L* = drain spacing.

The vertical seepage (q_v) was calculated using Darcy's law and the D-F assumptions (Skaggs, 1980) so that,

$$q_v = k_v(h_1 + d_v - h_v)/d_v \tag{10}$$

where k_v is the vertical hydraulic conductivity of the restrictive layer, h_1 is the water table depth above the restrictive layer, d_v is the thickness of the restrictive layer, and h_v is the piezometric head of the aquifer underneath the restrictive layer.

Lastly, the soil-water distribution in the profile is determined largely by the evapotranspiration and the depth of the root zone. When the moisture content of the soil in the root zone is greater than the wilting point, the ET is equal to potential evapotranspiration (PET) or maximum possible ET if sufficient water is available. If the ET is limited by the soil water conditions, then ET is equal to the upward flux of water as a function of the water table depth (which is determined from the SWCC). Water removed from profile through ET between storm events increases drawdown and changes the soil-water content in unsaturated zone allowing for more infiltration capacity in the soil (Skaggs, 1980).

More information on the governing equations to model soil-water processes in DRAINMOD including model components and input parameters can be found in Skaggs et al. (2012) and in the DRAINMOD Reference Report (Skaggs, 1980).

DRAINMOD Inputs Required

DRAINMOD was developed with the idea of using primarily measurable properties so that little calibration was required. However, like many process-based models, some of the detailed infiltration processes require specific soil properties or other inputs (such as the seepage parameters and root depths) that are difficult to measure precisely so that calibration is preferred

(Skaggs et al., 2012). The inputs required for DRAINMOD are broken into four categories: hydrology, soil, weather, and crops (Table 2.2).

Hydrology

The hydrology component includes a general input file describing the simulation options from the project settings. Hydrology also refers to the system design which describes the drainage capabilities. These include the inputs listed under system design, weir settings and seepage in Table 2.2.

Although most of the system design parameters are simple to understand, the spacing between drains and effective radius of the drain have modifications for bioretention applications suggested by Brown (2011). If there is not even spacing between drains, this parameter should be calculated as the effective drain spacing (bioretention surface area/drain pipe length). The effective radius accounts for the various opening sizes and configurations of the pipes (Skaggs, 1991). The effective drain radius is equal to the actual underdrain radius when surrounded by a gravel envelope but if a perforated pipe (with perforation openings equal to 1.5-2% of the wall area) is used then the effective radius should be set to 0.5 or 1.5 cm for drain pipes with 10 and 15 cm diameters respectively (Skaggs et al., 2012; Brown, 2011). In the case of bioretention, the actual distance from the surface to the impermeable layer represents the distance from the surface of the cell to the bottom of the gravel layer. The initial water table depth is set to be at the bottom of the cell. The maximum surface storage is the depth of the ponding layer. Kirkham's flow depth is the depth in which water no longer freely moves on the surface (Kirkham, 1957) and for smooth- surface bioretention cells is typically 0.5 or 1 (Brown, 2011).

The drainage coefficient is a parameter used to define a maximum drainage limit (cm/day) due to any limiting factors to drainage such as the diameter or slope of the drain, an orifice or valve, or other restrictions related to the drainage configuration. The initial values used for the drainage coefficients were set to the maximum measured drainage rate (Table 2.2). However, the drainage coefficient was used as a calibration parameter to remove the effect of pipe limitations and produce more outflow in the model.

The weir settings allow for the modeling of the IWS zone. In bioretention cells with an IWS zone, the weir depth is equal to depth from the soil surface at which the IWS zone begins. For cells without an IWS zone, the weir depth is simply the depth of the bioretention media. The bottom width of the ditch and ditch side slope were set to low values since there is no ditch conveying surface runoff (as is sometimes used in agricultural applications). However, to improve the internal processing of DRAINMOD-Urban, the bottom width of the ditch was increased slightly over previous DRAINMOD simulations.

Finally, the seepage parameters influence how much infiltrated water is exfiltrated from the system instead of exiting through the underdrain. The restricting layer represents the interface between the bottom of the bioretention cell and the surrounding soil. The vertical conductivity of the restricting layer describes the exfiltration rate into the underlying soil which can be measured as the saturated hydraulic conductivity of the underlying soil or as the drawdown rate. The other seepage parameters, the piezometric head of the aquifer (h_v) and the thickness of the restricting layer (d_v) used in Equation 10 are represented in the seepage diagram below (Figure I-1). The value of these inputs is unknown and therefore, they are primarily used as calibration parameters. However, the piezometric head is always smaller than the thickness of the restricting layer so that the hydraulic gradient directs flow out the bioretention cell.

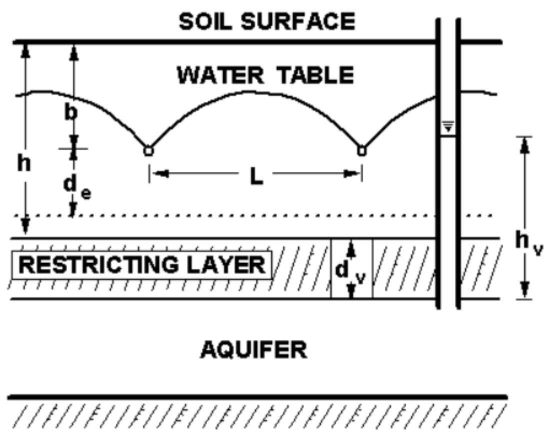

Figure I-1 Seepage diagram for DRAINMOD that describes the relationship between the piezometric head and the thickness of the restricting layer to the rest of the soil profile ("DRAINMOD 6.1 Help File," 2013).

Soil

The soil inputs are all derived from the SWCC of the bioretention media and the saturated hydraulic conductivity (K_{sat}) of each layer. The SWCC is manually entered into DRAINMOD which then uses a soil preperation program to internally process the remaining soil parameters such as volume drained, upward flux, and Green-Ampt infiltration parameters over varying water table depths. The water table depth versus volume drained is important to account for soil moisture in the bioretention cell as the internal water level fluctuates. The upward flux is the capillary movement at various water table depths. This is used when water is pulled into the root zone to meet ET demand. The upward flux is calculated in the soil preparation program using the Millington and Quirk procedure which estimates the unsaturated hydraulic conductivity and vertical saturated hydraulic conductivity from the SWCC.

The measured saturated hydraulic conductivity (K_{sat}) is entered directly to DRAINMOD for the respective bioretention media soil layer. The K_{sat} of the gravel layer underlying the bioretention media was estimated at 200 cm/hr. The K_{sat} of the sand layer in the UC cell was initially estimated at 15 cm/hr but was increased through calibration (Rawls et al., 1998; Domenico and Schwartz, 1990). The soil preparation program calculates an effective lateral saturated hydraulic conductivity (K_{eff}) as a depth-weighted K_{sat} from layers above the internal water level when calculating the Green-Ampt parameters at varying water table depths (Brown et al., 2013b). This K_{eff} is the conductivity used to calculate the drainage rate (Eqns. 7 or 9).

Weather

The weather inputs required are precipitation (hourly or daily) and minimum/maximum daily temperatures. The daily PET can be calculated in DRAINMOD using the Thornthwaite method with monthly correction factors, the heat index, site latitude, and the entered temperature files (Thornthwaite, 1948). PET can also be entered as a user-defined PET so that use of more detailed PET calculations is possible in substitution for the Thornthwaite method, which is the default.

Crop

The only crop parameter affecting bioretention is the root depth which is the top layer of soil with the most concentrated roots. This is used to evaluate seasonal changes in vegetation (therefore ET) over each year. This also identifies a boundary from which water can be removed to meet ET demands (Skaggs, 1991).

Contributing Area Runoff

The original DRAINMOD provided a contributing area runoff function which could be used to calculate the inflow to the system. First, DRAINMOD must be set up to represent a parking lot with limited drainage and storage by adjusting the Green-Ampt parameters to limit infiltration. The resulting surface runoff output file can be used as an input for the contributing area runoff utility along with the time of concentration, contributing area, and instantaneous unit hydrograph adjustment factor. Once this contributing area runoff file is created, it becomes an input for future DRAINMOD simulations which is added to the hydrology interface with the drainage area to bioretention area loading ratio (called field ratio in DRAINMOD). To be sure that this process creates similar inflow volumes compared to measured volumes, the runoff file must be calibrated prior to using it as an input for another simulation. This process is described in more detail in Appendix A.

Additional Inputs for DRAINMOD-Urban

DRAINMOD-Urban requires two additional inputs: 1-minute precipitation and 1-minute inflow to the bioretention cell. Guidance on the formatting required for these two text files are described in Appendix A. This 1-minute inflow file replaces the contributing area file described above to provide more accurate estimation or measurement of the surface runoff entering the system.

Outputs from DRAINMOD-Urban

DRAINMOD-Urban produces an output text file for the bioretention parameters on a 1-minute basis that contains the drainage, overflow, ET, and infiltration for each minute in the time series. Days with zero daily precipitation were not included in the output of the model. If precipitation occurred at any time-step, then the whole day is printed in the output file including zero time-steps during that day. The daily, monthly and yearly output files created by DRAINMOD are also produced as aggregated volumes. An automated spreadsheet was created through Excel VBA and used to process outputs received from DRAINMOD-Urban. This macro-enabled spreadsheet for processing data from DRAINMOD-Urban is freely available from the authors upon request and a description of how to use this spreadsheet for processing output data from DRAINMOD-Urban is found in Appendix A.

RESEARCH QUESTIONS

DRAINMOD-Urban as a model for enhanced bioretention modeling was evaluated in this dissertation from different perspectives. A summary of each chapter is outlined here, and research questions investigated in each chapter are listed below.

First, DRAINMOD-Urban is included in a comprehensive review of bioretention modeling (Ch. 1) that describes current modeling capabilities of many types of models applied to bioretention. Although DRAINMOD-Urban performance and application is not described until Chapter 2, it is still referenced in Chapter 1 as a beneficial addition to the review of bioretention modeling. Chapter 1identifies attributes that are required for advanced bioretention modeling and describes six models (DRAINMOD-Urban, GIFMod, HYDRUS, RECARGA, MUSIC, and SWMM) in detail related to their hydrologic and hydraulic processes.

Next, the performance of DRAINMOD-Urban was assessed in Chapter 2 by comparing measured and modeled hydrographs. The performance of DRAINMOD-Urban was also compared to the original DRAINMOD model through both a top-down and bottom-up approach to understand the effects of calibrating the model to water balance volumes as opposed to hydrographs. This serves as a foundational performance study of DRAINMOD-Urban and is used as a baseline for comparison in Chapters 3 and 4.

In Chapter 3, DRAINMOD-Urban was compared to the well-known hydrologic model SWMM to investigate the validity of the calculations of the SWMM LID module and the ability of a watershed model to adequately simulate internal processes of a single bioretention cell.

Lastly, in Chapter 4, the sensitivity of DRAINMOD-Urban soil parameters was examined. Pedotransfer functions have been used in modeling efforts to gain required soil inputs from easily-measured soil properties such as soil texture. These functions were used to derive the

SWCC and saturated hydraulic conductivity (K_{sat}) which are required soil parameters in DRAINMOD-Urban. Simulations with measured soil parameters were compared to those calculated by pedotransfer functions to understand the level of detail required for adequate simulation of flow through a bioretention system.

- Chapter 1: Modeling Bioretention Stormwater Systems: A Review of Current Models and Research Needs
    - *Research Questions:*
        - *What models are available for modeling bioretention?*
        - *What are attributes required for advanced bioretention modeling?*
        - *How are the fundamental hydrologic processes of a bioretention cell represented in models well-suited for bioretention applications?*
        - *What future improvements are required in this field?*
- Chapter 2: Enhanced Bioretention Cell Modeling: Moving from Water Balances to Hydrograph Production
    - *Research Questions:*
        - *Can DRAINMOD-Urban accurately produce drainage and overflow hydrographs?*
        - *How do parameter sets calibrated to total volumes in DRAINMOD perform when temporal resolution is downscaled in DRAINMOD-Urban? Conversely, how do parameter sets calibrated to hydrographs in DRAINMOD-Urban perform at estimating total volumes in DRAINMOD?*

- Chapter 3: Comparison of DRAINMOD-Urban for Bioretention Modeling with SWMM LID Module
    - *Research Questions:*
        - *How does each model (DRAINMOD-Urban and SWMM) perform at producing drainage and overflow hydrographs?*
        - *Which model is better at describing hydrologic behavior of a bioretention cell? Which model is better at describing the water balance volumes from a bioretention cell?*
        - *What applications are best suited to DRAINMOD-Urban and SWMM in relation to bioretention modeling?*
- Chapter 4: The Role of Estimated Soil Parameters on Bioretention Modeling: A Sensitivity Study
    - *Research Questions*
        - *Do various pedotransfer functions that have performed well for coarse-textured soils represent measured bioretention soil properties?*
        - *Can pedotransfer functions for the SWCC and K_{sat} be used in place of measured values in DRAINMOD-Urban to reduce soil input complexity without hindering model performance?*

CHAPTER I

MODELING BIORETENTION STORMWATER SYSTEMS: A REVIEW OF CURRENT MODELS AND RESEARCH NEEDS

1.1 Abstract

Low Impact Development (LID) refers to new sustainable methods of approaching urban stormwater management that have been designed to return urban hydrology to predevelopment conditions. Many modeling studies have focused on lumped benefits of LID instead of the individual practices yet there is still much to be learned about the functionality and optimization of multiple types of LID practices. This review focuses on the modeling of one commonly used LID practice, bioretention cells. Many models still incorporate simplifications and lumped parameters that do not fully account for fundamental physical processes occurring in the bioretention cells. This review summarizes applications and notable features of bioretention models used in previous studies with the goal of identifying key research needs. Although modeling water quality of bioretention cells is also valuable, this review focused solely on hydrology as improvements in methods for modeling flow processes will also affect water quality loading predictions. Advanced bioretention models were identified by meeting criteria related to hydrologic modeling and bioretention components. Hydrologic and hydraulic processes of each advanced model were assessed in relation to the governing equations used to model each water balance component within a bioretention cell. Analysis of infiltration processes in each model identified HYDRUS and GIFMod as the only models that use Richards' equation for determining infiltration under variably saturated conditions. The other models evaluated used a simplified version of Richards' equation, the Green-Ampt equation, which assumes saturated soil. This study identified limited drainage configurations by most models except DRAINMOD-Urban.

Underdrains and internal water storage (IWS) zones are commonly used in practice and models need to be updated to represent various drainage designs. Another area for improvement is in the consideration of vegetation and evapotranspiration (ET) in the model. Finally, more calibration and validation studies need to be completed to build confidence in model results. Identifying models with advanced bioretention modeling features and educating modelers of the processing equations for each component of the water balance, the input requirements in each model, and other model advantages/disadvantages will help modelers choose the appropriate model for a given bioretention application. Further, the improvements suggested in this review will improve future directions of bioretention modeling.

1.2 Introduction

1.2.1 Background

Urban runoff has been shown to cause a range of environmental problems such as stream channelization, deterioration of stream habitat and decreased water quality (Dietrich et al., 2017; Liu et al., 2014a; Asleson et al., 2009). To combat these problems, alternative methods of stormwater management have been developed to reduce the volume and peak flows of urban runoff by increasing infiltration and evapotranspiration (ET). Many of these approaches also focus on improving water quality through filtration, sedimentation, sorption, and biological uptake (Hatt et al., 2009). The goal is to return as close as possible to pre-development flow and water quality conditions and, thus, re-establish the natural hydrology of the landscape.

This concept, referred to as Low Impact Development (LID) or Water Sensitive Urban Design (WSUD), is an urban-planning technique that focuses on all methods of reducing the effects of urbanization, from reducing impervious areas during planning, to conserving natural resources and public awareness/education (Kaykhosravi et al., 2018; Fletcher et al., 2014; Liu et al., 2014a). Another LID concept is the use of improved ecological engineering structures called green infrastructure (GI) (Kaykhosravi et al., 2018; Liu et al., 2014a). GI integrates traditional engineering design with natural materials to develop solutions to reduce impact on the environment. Typical examples of GI include permeable pavement, green roofs, rain barrels, and bioretention cells (Kaykhosravi et al., 2018; Dietrich et al., 2017; Liu et al., 2014a; Davis et al., 2009). When describing individual practices, GI is often also referred to as LID practices, stormwater best management practices (BMPs), stormwater control measures (SCMs) or sustainable urban drainage systems (SUDS) (Fletcher et al., 2014). Bioretention is the predominant choice of LID in the U.S. because it can control the volume, rate, and quality of stormwater runoff (Akan, 2013).

Bioretention cells are systems used to capture and filter stormwater runoff which is released through exfiltration into the surrounding soil (and eventually groundwater aquifers), drainage (for systems with underdrains), and plant uptake (i.e. ET). The schematic of a typical bioretention cell can be found in Figure 1.1. A bioretention cell is constructed in layers of infiltrative material: the base is filled with gravel and a perforated drainage pipe to remove excess water from the cell, sometimes a choking sand layer is then placed above the gravel. Next, the bioretention media, a sandy soil mix that allows for plant growth and high infiltration rates, constitutes the largest layer. On top of the bioretention media is often a small mulch layer and a ponding zone that allows for pooling as water infiltrates into the system. Lastly, bioretention cells are often planted with plants that can withstand both wet and dry periods with minimal maintenance (Dagenais et al., 2018; Payne et al., 2018).

Various drainage configurations for the underdrain pipe are possible. One common configuration is an upturned elbow which creates and internal water storage zone (IWS, Figure 1.1). Internal water storage zones are often used to promote peak flow reduction, to enhance exfiltration, and to create anaerobic conditions to increase nitrogen removal (Brown and Hunt, 2011b).

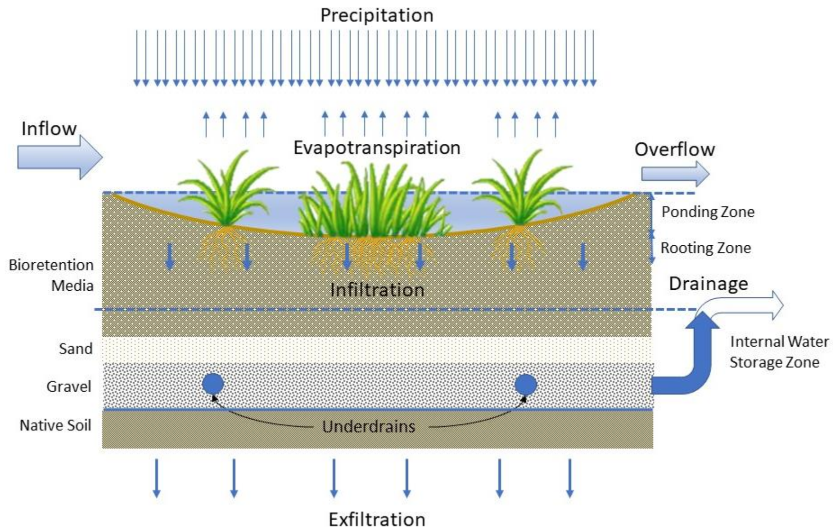

Figure 1.1. Schematic of typical bioretention cell

Bioretention systems have been widely accepted within the engineering community due to many field studies demonstrating substantial volumetric reductions (Olszewski and Davis, 2013; Brown and Hunt, 2012; Davis et al., 2012; Brown and Hunt, 2011a; Davis, 2008; Hunt et al., 2006) and water quality improvement (Kluge et al., 2018; Wan et al., 2018; Lucke et al., 2017; Wang et al., 2017; Yang et al., 2014; Brown and Hunt, 2011b; Chapman and Horner, 2010; Ergas et al., 2010; Li and Davis, 2009; Hunt et al., 2008; Li and Davis, 2008b; Davis, 2007). Many studies have been conducted on field sites to assess performance of bioretention cells with varying design attributes (Al-Ameri et al., 2018; Wan et al., 2018; Jiang et al., 2017; Lopez et al., 2016; Lucke and Nichols, 2015; Paus et al., 2014; Brown et al., 2013a; Komlos and Traver, 2012; Brown and Hunt, 2011a; 2010; Li et al., 2009; Line and Hunt, 2009; Davis, 2008; Hunt et al., 2006; Hsieh and Davis, 2005). Even mesocosm or column studies have received widespread attention in bioretention research to assess hydrologic and water quality performance under more controlled conditions (Wang et al., 2018; Goh et al., 2017; Liu and Fassman-Beck, 2017; Ray et al., 2015; Wadzuk et al., 2015; Liu et al., 2014b; Payne et al., 2014; Palmer et al., 2013; Good et al., 2012; Lucas and Greenway, 2011b; 2011a; 2011c; Stander and Borst, 2010; Li and Davis, 2008a; Lucas and Greenway, 2008; Hsieh et al., 2007b; 2007a).

Yet, significantly fewer studies have addressed modeling of bioretention systems. Modeling of these systems is important to be able to assess the performance of a system before installation, to review the applicability of design guidelines to various scenarios and climates, and to be able to scale local impacts to the larger watershed. Due to the overwhelmingly positive reports from the research conducted thus far, bioretention systems have been widely adopted, often before all the effects of these systems can be researched in field and mesocosm studies. Process-based modeling provides a way to check any anomalies in initial observations or assumptions and to make adjustments while still considering the physical properties of the site (Heasom et al., 2006). Therefore, there is a need for a comprehensive, process-based hydrologic model to predict the performance of bioretention cells for design and evaluation purposes (Meng et al., 2014).

There are many opportunities for improvement of field and mesocosm studies through the knowledge gained in bioretention modeling. Bioretention systems have been installed in locations without regional design standards so designers must refer to standards from other regions (Davis et al., 2009). Modeling can help adjust design standards to better fit regional climate, vegetation, and other local characteristics. Additionally, little is known about the long-term effects of these bioretention systems.

Three studies have demonstrated effective performance as long as 8-10 years (Li and Lam, 2015; Lucke and Nichols, 2015; Paus et al., 2014). Long-term modeling could identify the limits of a bioretention cell under various climate and design scenarios (Hathaway et al., 2014; Brown et al., 2013b).

Furthermore, what are the effects of these systems at the watershed scale? Many times, the installation and location of bioretention systems is opportunistic, such as when current infrastructure is failing, or a new development is constructed which creates a piecemeal approach to stormwater management (National Research Council, 2009). As more SCMs like bioretention are added to a watershed, the cumulative effects must also be understood. Advances in bioretention modeling could help identify the effects of multiple bioretention cells in a catchment and the optimal locations for bioretention cells (Lee et al., 2012). Additionally, addressing watershed effects through widespread, systematic installation of bioretention cells would require a lot of time and money. This is a case where modeling would serve as a first step to address catchment-scale processes prior to field studies. However, it is imperative that bioretention modeling first be improved at the site-scale before modeling can be accomplished at the watershed scale to avoid compounding errors. These are all future applications of bioretention modeling, but more research is needed to meet these needs.

1.2.2 Previous Literature Reviews

Three reviews (Liu et al., 2014a; Roy-Poirier et al., 2010; Davis et al., 2009) have summarized bioretention research and future needs. All three reviews have provided brief overviews of bioretention modeling but have also listed it as a concern for future research. Roy-Poirier et al. (2010) described the RECHARGE/RECARGA models, a study by Heasom et al. (2006) using HEC-HMS, and two models designed for water quality analysis of bioretention. Davis et al. (2009) did not mention any specific models but instead merely listed computational modeling as a future need in the bioretention field. Similarly, Dietz et al. (2007) reviewed multiple LID practices (bioretention, green roofs, and permeable pavements) but only described RECARGA and WinSLAMM as potential design tools and concisely mentioned improving models as a future need. It should be noted that bioretention is a new technology and very few models for bioretention were available prior to 2010, suggesting these reviews excluded substantial amounts of new research in this area. While Liu et al. (2014a) includes a review of more models than the aforementioned older reviews, including SWMM, HydroCAD, DRAINMOD and IDEAL, it is just one section of a larger review of bioretention studies.

Elliot and Trowsdale (2007) was one of the first LID literature reviews to focus specifically on modeling of LID practices. This study identified 10 models used for LID either explicitly or implicitly (MOUSE, MUSIC, WinSLAMM, SWMM and WBM for bioretention) and compared them based on model features such as spatial and temporal resolution, runoff generation and routing, and intended uses of the model. At the time of this study, SWMM could only model LID implicitly prior to the upgrade with dedicated LID modules in 2010 (Rossman, 2010). Kaykhosravi et al. (2018) improved upon the Elliot and Trowsdale (2007) study by identifying new models that have been developed since the first review such as GIFMod, HYDRUS and an updated SWMM. This study gives an overview of 11 models used for LID practices and describes general features of the models, hydrological processes of LID that help quantify the water balance, infiltration and runoff generation techniques, and flow routing hydraulics. Li et al. (2017) completed a comprehensive review of catchment-scale modeling and monitoring LID studies describing methods and key results. However, only 12 of the 31 modeling studies mentioned bioretention or rain gardens and only four of those 12 focused on bioretention results instead of lumped LID benefits. Jayasooriya and Ng (2014) focused on models that provided economic analysis of LID practices. Although these reviews have focused specifically on modeling of LID practices, they have not been devoted to bioretention alone.

Concentrating on bioretention allows a more detailed look at the internal processes of the system and how to overcome some of the challenges of modeling the complex soil-water interactions of bioretention systems. Furthermore, none of these modeling reviews detailed what input parameters are required for each bioretention model, although the number and complexity of input parameters can limit model use. For these reasons, bioretention warrants its own review of available models and modeling techniques. The objectives of this review will be to give a broad overview of available models for bioretention and a detailed examination of hydraulic and hydrologic processes in models best suited for bioretention modeling. This review will be valuable to the field of bioretention modeling by identifying strengths and weaknesses of each model and areas for future improvement.

1.2.3 Review Process and Structure

Although there are also many models being used to address water quality improvement from bioretention, this review will describe only models used for bioretention cell hydrology and hydraulics. It is important to confront errors in modeling bioretention hydrology before modeling of water quality can be improved because flow volumes, peaks, and timing of hydrographs will affect nutrient loadings, plant uptake, and microbial behavior. Furthermore, reduction of pollutant loadings is often attributed to reduced runoff volumes rather than biogeochemical processes (Jefferson et al., 2017; Wilson et al., 2015; Davis et al., 2009).

First, 23 models capable of modeling bioretention cell hydrology were identified and summarized in Tables 1.1 and 1.2. Models were split into three categories based on their intended uses: planning/assessment tools, manual mathematical models, and process-based computational models. Application of planning tools and manual mathematical models are briefly discussed. Only process-based computational models were selected for further analysis in this study because they use governing equations to describe fundamental hydrologic processes. This allows for investigation of hydrologic pathways in a bioretention cell as opposed to lumped parameter models that give generic estimates of runoff reduction potential. A brief description introduces each model including the main objective of the model, previous studies, general information about hydrologic and hydraulic processes, and any other notable features.

Next, three attributes of process-based hydrologic modeling were identified (simulation type, temporal scale, and spatial scale). Preferred methods for these attributes to be classified as advanced modeling criteria are continuous, long-term simulations, and sub-hourly timesteps (Figure 1.2). However, many hydrologic/hydraulic models meet these requirements without explicitly being designed for bioretention. Therefore, to be considered in this study models must also contain processes explicitly developed for bioretention.

Previous research has identified shortcomings of many bioretention models and suggested that improving computational modeling of these systems is an ongoing research need (Liu et al., 2014a; Meng et al., 2014; Akan, 2013; Brown, 2011). Recommended criteria for advanced bioretention modeling were chosen to address these model deficiencies which included improved infiltration processes through the use of Richards' equation or soil water retention, drainage configurations that represent underdrains and IWS zones, incorporation of vegetation such as water uptake processes and ET calculations, and production of output hydrographs. To be considered a model well-suited for bioretention in this study, the model must meet four out of seven recommended advanced bioretention model attributes (Figure 1.2). The six models which meet these criteria were evaluated in further detail concerning the hydrologic and hydraulic processes associated with each water balance component.

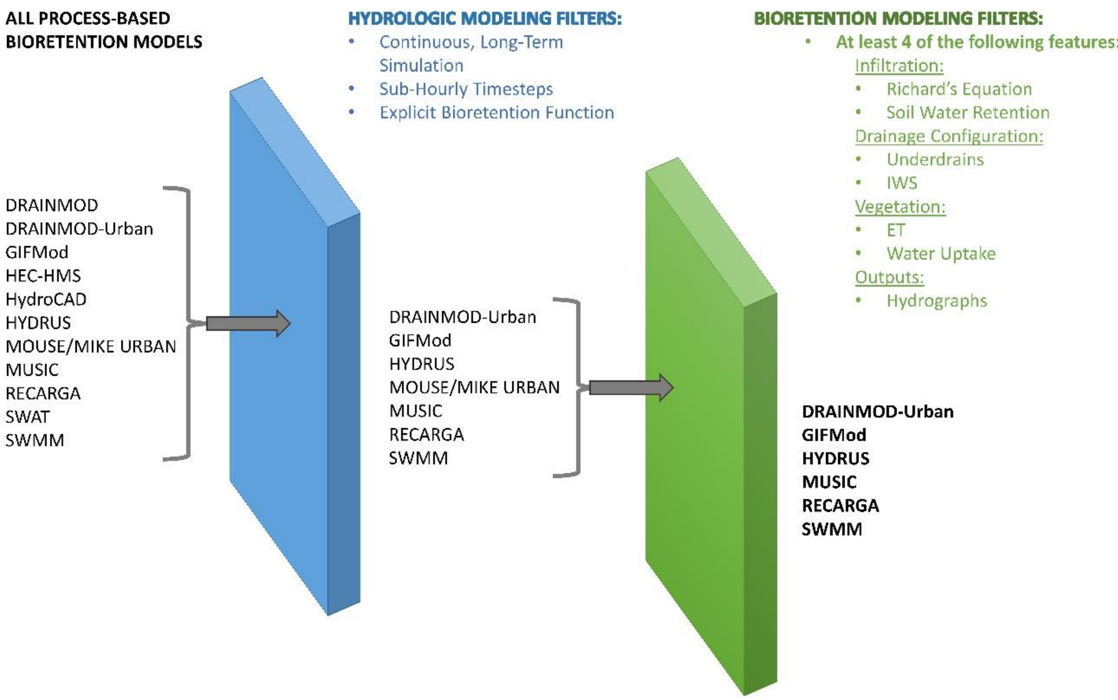

Figure 1.2. Review process and filtering procedure to determine models best suited for advanced bioretention modeling.

Table 1.1. Descriptions of process-based computational models relevant to modeling bioretention cells

Model Name	Released	Latest Version	Primary Author/ Organization	Primary Objective	References
DRAINMOD	1980	2013, v.6.1	Skaggs (1978, 1980); North Carolina State University	Simulate long-term hydrology of poorly-drained agricultural soils; later applied to bioretention cells by Brown et al. (2013)	Documentation: https://www.bae.ncsu.edu/agricultural-water-management/drainmod/manuals/; https://www.drainmod.org/drainmod_help/
					Download: https://www.bae.ncsu.edu/agricultural-water-management/drainmod/download/
					Application: Winston (2015); Brown et al. (2013); Brown (2011)
DRAINMOD-Urban	In Progress	In Progress	Lisenbee et al., 2020; North Carolina State University	Update DRAINMOD model to accept finer resolution inputs and outputs to better represent urban hydrology in bioretention cell applications	Documentation: the same as DRAINMOD (above); Contact NC State for DRAINMOD-Urban updates
					Download: Contact Mohamed Youssef (NC State)
					Application: Lisenbee et al., 2020
GIF-Mod	2016	2017, v.1.2	Massoudieh (2017); Massoudieh and Aflaki (2016)	Evaluate the performance of stormwater GI and other BMPs including hydraulics, particle transport, and constituent fate and transport	Documentation: www.gifmod.com
					Download: https://github.com/USEPA/GIFMod
					Application: Massoudieh et al. (2017)
HEC-HMS	1998	2018, v.4.3	US Army Corps of Engineers	Simulating hydrologic processes of watersheds; applied to bioretention cells by Heasom et al. (2006)	Documentation: https://www.hec.usace.army.mil/software/ hec-hms/documentation.aspx
					Download: https://www.hec.usace.army.mil/software/hec-hms/downloads.aspx
					Application: Khaniya et al. (2017); Heasom et al. (2006)
HydroCAD	1986	2011, v10	HydroCAD Software Solutions LLC	Performs a wide range of hydrology and hydraulics techniques; applied to bioretention by Lucas (2010)	Documentation: https://www.hydrocad.net/info.htm
					Application: Lucas (2010)
HYDRUS	1995	2018, v.4.17	PC-Progress; Simunek, Sejna, & van Genuchten	Analysis of water flow and solute transport in variably saturated porous media; applied to bioretention by Meng et al. (2014)	Documentation: https://www.pc-progress.com/en/Default.aspx?H1D-description#k1
					Download: https://www.pc-progress.com/en/Default.aspx?H1d-downloads
					Application: Li et al. (2018); Stewart et al. (2017); Liu (2016); Meng et al. (2014)

Table 1.1 (continued). Descriptions of process-based computational models relevant to modeling bioretention cells

Model Name	Released	Latest Version	Primary Author/ Organization	Primary Objective	References
MOUSE/ MIKE URBAN	1985	2016	DHI Water and Environment	Simulation of hydrology, hydraulic, water quality and sediment transport in urban drainage and sewer systems	Documentation: https://www.mikepoweredbydhi.com/products/mike-urban Application: Xie et al. (2017); Li and De Costa (2016)
MUSIC	2001	2017, v.6.3	Monash University; eWater	Evaluate drainage systems with treatment devices for optimal cost, hydrology and water quality improvement	Documentation: MUSIC User Manual: https://wiki.ewater.org.au/display/MD6/Bioretention+Systems Download: https://ewater.org.au/products/music/ Application: Gagrani et al. (2014); Hamel and Fletcher (2013, 2014); Imteaz et al. (2013); Burns et al. (2012); Dotto et al. (2011); Elliott et al. (2009); Wong et al. (2002, 2006)
RECARGA	2002	2004; v.2.3	Dussaillant et al., 2003; University of Wisconsin	Design tool for evaluating the performance of bioretention facilities, raingarden facilities, and infiltration basins	Documentation: https://dnr.wi.gov/topic/stormwater/standards/recarga.html; https://publications.aqua.wisc.edu/product/design-guidelines-for-stormwater-bioretention-facilities/ Download: https://dnr.wi.gov/topic/stormwater/standards/recarga.html Application: Boanca et al. (2018); Gao et al. (2018); Montgomery et al. (2010); Turney and Neilson (2010); Muthanna et al. (2007); Dussaillant et al. (2003)
SWAT	1990	2016	Jeff Arnold (USDA-ARS) and R. Srinivasan (Texas A&M)	Evaluate land use changes and BMP development on water quantity and quality of surface and ground water in agricultural watersheds	Documentation: https://swat.tamu.edu/docs/ Download: https://swat.tamu.edu/software/ Application: Seo et al. (2017); Jeong et al., (2010); Christianson (2003)
SWMM	1971	2018; v.5.1	US EPA	Model runoff generation and routing within an urban catchment; LID features added in 2010	Documentation: https://www.epa.gov/water-research/storm-water-management-model-swmm; Rossman (2017); Rossman and Huber (2016); Rossman (2010) Download: https://www.epa.gov/water-research/storm-water-management-model-swmm Application: Kim et al. (2019); Tiveron et al. (2018); Yang and Chui (2018); Zhang et al. (2018 a, b); Avellaneda et al. (2017); Gulbaz and Kazezyilmaz-Alhan (2017c); Liu and Fassman-Beck (2017); Lynn et al. (2017); Li and Lam (2015); Rosa et al. (2015); Sun et al. (2014, 2011); McCutcheon and Wride (2013); Aad (2010); Zhang et al. (2010); Bosley (2008)

Table 1.2. Descriptions of planning tools/preliminary design models relevant to modeling bioretention cells

Model Name	Released	Latest Version	Primary Author/ Organization	Primary Objective	References
Green Values National Stormwater Management Calculator	2004	2017	Center for Neighborhood Technology	Quick comparison of performance and cost of GI versus conventional stormwater practice	Documentation: https://greenvalues.cnt.org/calculator/ downloads/methodology.pdf
					Online Tool: https://greenvalues.cnt.org/calculator/calculator.php
L-THIA/LID	2000	2015	Purdue University	Spreadsheet tool to simulate runoff and water quality with LID practices	Documentation: https://engineering.purdue.edu/mapserve/LTHIA7/lthianew/lidIntro.php; https://engineering.purdue.edu/mapserve/LTHIA7/documentation/doc_index.html
					Online Tool: https://engineering.purdue.edu/mapserve/LTHIA7/lthianew/lidIntro.php
SUSTAIN	2009	2014, v.1.2	US EPA	Planning tool for cost-effectiveness of stormwater runoff and pollution mitigation	Documentation: US EPA (2013, 2011, 2009)
					Download: https://www.epa.gov/water-research/system-urban-stormwater-treatment-and-analysis-integration-sustain
					Application: Mao et al. (2017); DeGasperi (2013); Lee et al. (2012)
US EPA National Stormwater Management Calculator	2009	2018, v.1.2	US EPA	Estimates annual stormwater runoff with and without GI to plan for stormwater retention targets	Documentation: https://www.epa.gov/water-research/national-stormwater-calculator
					Online Tool: https://swcweb.epa.gov/stormwatercalculator/
WBM	2003	2003	BC Partnership for Water Sustainability	Web-based tool for planning of water quality assessment with GI	Documentation: https://waterbalance.ca/tool/water-balance-model/; https://waterbalance.ca/technical_manual/
					Online Tool: http://waterbalance.ca/wbm/
WinSLAMM	1998	2019, v.10.4.1	Pitt, 1998; Pitt & Voorhees, 2002; PV & Associates, LLC	Planning tool for runoff volume and contaminant loading	Documentation: PV & Associates (2015); Pitt (2006); Pitt & Voorhees (1995)
					Download: PV & Associates. WinSLAMM. Available online: http://winslamm.com
					Application: Talebi and Pitt (2012); Pitt and Voorhees (2002)

1.3 Model Descriptions

1.3.1 Planning/Assessment Tools

A number of models have been created as planning tools for a quick assessment of the effect of bioretention cells in a watershed. Generally, these models require minimal expertise or training by users which makes them popular options for initial assessment of a site. These models do not simulate hydrological processes within the bioretention cells but instead use lumped parameters for a general estimation of the runoff reduction potential, water quality, and cost-benefit analysis to support decision making. For example, the Center for Neighborhood Technology describes the Green Values National Stormwater Calculator as a "first approximation of the hydrologic and financial conditions for a site" (Center for Neighborhood Technology, 2007). Similarly, the U.S. Environmental Protection Agency (EPA) National Stormwater Management Calculator is a simplified version of SWMM that only considers overland flow, infiltration and evaporation with the main goal of assessing if developers meet certain stormwater retention targets (Rossman and Bernagros, 2018).

The U.S. EPA also developed the System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) for the placement of LID practices within a watershed while also optimizing cost and water quantity and quality performance. SUSTAIN combined many algorithms from other LID models including SWMM but only certain criteria are used in the optimization modules. Some case studies have demonstrated model setup and calibration in locations across the United States: King County, WA, Kansas City, MO, Louisville, KY and Albuquerque, NM (Shoemaker et al., 2013; Lee et al., 2012; Shoemaker et al., 2011; DeGasperi, 2009).

Other models that provide quick assessment of hydrology and water quality benefits of LID (including bioretention) are L-THIA/LID (Long Term Hydrologic Impact Analysis), developed by

Purdue University as a web-based tool for long-term hydrologic assessment LID practices, WBM (Water Balance Model), created as an online tool for scenario comparison, and UEM (Urban Ecohydrological Model), which is a lumped parameter model that aggregates all bioretention cells in a watershed to a single parameter to evaluate ecological and stream health associated with bioretention design scenarios ("Water Balance Model Powered by Qualhymo: Technical Manual," 2019; Wright et al., 2018; "L-Thia Low Impact Development Spreadsheet," 2015).

Lastly, some models listed put more emphasis on water quality such as IDEAL (Integrated Design, Evaluation and Assessment of Loadings) which was developed to predict water quality improvement from LID. IDEAL can produce detailed outputs of each bioretention cell such as hydrographs, sedigraphs, chemigraphs, and pollutographs (Alexander et al., 2011). WinSLAMM (Source Loading and Management Model) was designed to provide simple pollutant mass discharges and runoff volumes for a variety of stormwater control practices and development scenarios (Pitt and Voorhees, 2004). WinSLAMM also has a large focus on water quality because it emphasizes small storm hydrology (better for water quality analysis) and particulate washoff.

1.3.2 Manual Mathematical Models

Manual mathematical models are comprised of a series of equations to describe bioretention cell behavior without any user interface or computer programming to automatically calculate said equations. He and Davis (2011) used Richards' equation to create a 2D mechanistic model which can simulate unsteady-state, variable saturated flow conditions. This detailed model is useful in many areas of bioretention design by examining the effects of underdrains, media composition, surrounding soil properties, and sizing properties on the water balance of the bioretention cell.

Akan (2013) suggested a physically-based mathematical methodology for designing the ponding and storage zones in a bioretention system. The soil-water processes within a bioretention system were described in phases demonstrating varying levels of saturation in the cell. A two-parameter Gamma function was used to create an inflow hydrograph from only the total runoff volume and the peak flow rate. Next, a finite-difference scheme was employed to solve the governing equations, including Green-Ampt for infiltration and Darcy's law for seepage. This numerical model was used to create charts that can be applied in the sizing of bioretention cells.

Zhang and Guo (2013) developed an analytical probabilistic expression (APE) to model the long-term average stormwater capture efficiency of bioretention systems. This study avoids using the Howard's conservative assumption that is applied to other probabilistic approaches and often leads to underestimation of the capture efficiencies. This APE provides an approximate expected value of the water content in the bioretention cell after the preceding rain event which is used as an initial condition for the randomized rainfall event being analyzed. APE was compared to SWMM to assess its validity with good results. Therefore, this APE can contribute in preliminary design of bioretention cells by analyzing the expected water contents for various surface depression depths.

Lastly, Barbu and Ballestero (2015) developed a sequence of physically-based equations that were selected to find the SWCC and relative hydraulic conductivity function for bioretention media which are required for calculation of unsaturated flow using Richards' equation. Both the moisture retention curve and the relative hydraulic conductivity function are soil properties that are very difficult and time-consuming to measure; therefore, many studies assume saturated conditions in bioretention cells. The methodology presented by Barbu and Ballestro (2015) provides a way to consider unsaturated flow through bioretention cells and can be integrated in current stormwater design models.

1.3.3 Process-Based Computational Models

1.3.3.1 DRAINMOD

DRAINMOD was originally developed as a long-term, continuous simulation, water management model to simulate poorly or artificially drained agricultural soils. Bioretention cells with high internal water tables during storm events behave similarly to these agricultural fields and drain through porous underdrain pipes like soil tile drains. Furthermore, this model uses the soil-water characteristic curve (SWCC) so that the effect of soil moisture in the bioretention cell profile between storm events can be considered in soil-water processes that make up the water balance. This is also one of few models with the capability to model the IWS or submerged zone applied in some bioretention cells. Brown et al. (2013b) was the first to apply this model to four bioretention cells in North Carolina with good calibration of inflow, drainage, and overflow (Nash-Sutcliffe Efficiency, NSE>0.71). In 2014, the North Carolina cells were modeled under changing climate conditions (Hathaway et al., 2014). Winston (2015) also tested DRAINMOD on three more bioretention cells in Ohio which maintained good agreement with measured volumes for each water balance component (NSE>0.71). It should be noted that these models were run at a low temporal resolution of daily or hourly time steps with outputs summarized for daily, monthly and yearly totals.

1.3.3.2 DRAINMOD-Urban

Although DRAINMOD was shown to be an effective model for bioretention cells when calculating volumes of water balance components, it could only produce daily outputs as the smallest time step. Therefore, DRAINMOD was unable to output hydrographs to examine peak flow rates and allow for integration with other watershed models. To better represent the flashy nature of urban hydrology, DRAINMOD was updated to accept inputs and produce outputs at as small as 1-minute intervals. This updated model was termed DRAINMOD-Urban. Lisenbee et al.

(2020) showed that DRAINMOD simulations performed by Winston (2015) did not represent measured drainage hydrographs well, even if volumes were well-calibrated. DRAINMOD-Urban was then calibrated to better represent measured drainage hydrographs (Ch. 2). Results showed good agreement of the model (NSE=0.60) especially considering the high-resolution output (1-minute intervals). DRAINMOD-Urban has also been compared to SWMM and evaluated using pedotransfer functions to substitute for required soil properties in the model (Ch. 3 & Ch. 4 respectively).

1.3.3.3 GIFMod

The GI Flexible Model (GIFMod) was developed as a continuous, process-based model that is flexible in that it can be applied to a wide range of GI practices and allows the user to define the structure and complexity of the model. The structure is composed of a series of blocks connected by interfaces that represent each component of the GI system (soil layer, stream segment or storage). A water balance is conducted on each of these blocks at a sub-hourly time step and the interfaces between blocks are governed by a number of provided equations. The three main mechanisms of this model include hydraulics, particle/colloid transport and dissolved or particle-bound contaminant transport (Massoudieh and Aflak, 2017). The hydraulics component can simulate flow through storage layers or structures, porous media under saturated and unsaturated conditions, pipe flow, overland flow and ET. GIFMod allows for user-defined head-storage and head-flow relationships as well as predefined relationships for each block type. For soil blocks, this function can be populated by default or user-input soil parameter values. Massoudieh et al. (2017) describes the model as applied to two bioretention cells connected in series. The initial modeling results showed good model agreement for the upper rain garden (NSE=0.83) but reduced performance in the lower rain garden (NSE=0.49). However, more rigorous calibration with an extended dataset was suggested by Massoudieh et al. (2017).

1.3.3.4 HEC-HMS

The Hydrologic Engineering Center- Hydrologic Modeling System (HEC-HMS) was developed in 1998 (as HEC-1 originally) by the U.S. Army Corps of Engineers (USACE) as a continuous, numerical model to simulate hydrologic processes of dendritic watershed systems. It is widely used in industry for planning and design in flood forecasting, evaluating hydraulic conveyance and controls, and erosion and sediment routing studies (U.S. Army Corps of Engineers, 2018). Heasom et al. (2006) used HEC-HMS to model the flow through a bioretention cell by replicating it as a reservoir which serves a storage capacity for flow from two sub-basins (representing pervious and impervious surfaces in the catchment area). The reservoir (bioretention basin) is drained as weir flow. HEC-HMS was used to model bioretention cells in this study because it is a common hydrologic model that offers widely accepted methods for infiltration and hydraulic routing. Also, the output hydrographs can easily be compared to measured water levels in bioretention cells. However, Heasom et al. (2006) does admit that the setup of the bioretention cell with a diversion element and further post-processing of combined outflow is not straightforward. Another case study (Khaniya et al., 2017) used HEC-HMS to model a rain garden but even these authors admit to limitations of HEC-HMS such as event simulation and limited runoff generation options.

1.3.3.5 HydroCAD

HydroCAD is a proprietary hydrological and hydraulic model employed widely in industry. Lucas (2010) described how to apply HydroCAD to routing outflow from many bioretention cells in a catchment to reduce combined sewer overflows (CSO). HydroCAD allows for rating curves to be applied to orifices so that the hydraulic grade line can be modeled through the bioretention cell profile (Lucas, 2008). Although HydroCAD is a design storm model, it was compared with a continuous simulation model, SWMM. Outflow hydrograph volumes and peak flows were compared with good agreement.

1.3.3.6 HYDRUS

HYDRUS-1D is a long-term continuous model that was originally developed to model flow and transport through variably saturated porous media. Its benefits are flexible flow boundary conditions, a small calculation time step, and unlimited simulation time (Meng et al., 2014). Meng et al. (2014) was the first to apply HYDRUS-1D to two bioretention cells in Beijing that had been continuously monitored for 33 artificial rainfall events and five natural rainfall events. The measured infiltration rate over time was compared to the outputs of HYDRUS-1D for model validation. Following model validation, design parameters were optimized with the model to evaluate performance under different conditions. Li et al. (2018) also applied HYDRUS-1D to three bioretention cells for optimization of parameters, such as media characteristics and thickness, with good model agreement for water volume (NSE=0.86-0.90). Lastly, the two-dimensional Richards' equation model (HYDRUS-2D/3D) was applied to a bioretention cell in Ohio to calculate a mass balance of outflow, evaluate subsurface water dynamics, and assess model sensitivity to soil properties (Stewart et al., 2017). This study also addressed bioretention cell effects on CSOs and groundwater. The water levels measured from nearby wells had good agreement with the modeled water levels over the entire three-year period (RMSD=0.026-0.12 m).

1.3.3.7 MOUSE/MIKE URBAN

The Model for Urban Sewers (MOUSE) was developed by Danish Institute of Hydrology in 2002. The model has since been updated to MIKE URBAN which is capable of running simulations using the MOUSE, SWMM, or MIKE-1D engine. In 2016, the newest version of MIKE URBAN updated the user interface to incorporate dedicated LID controls including bioretention. For LID practices, it is noted that only the MIKE-1D engine is used and most LID practices can be represented by a “soakaway” node (DHI, 2017). A case study on application to a rain garden is presented by Li and De Costa (2016). Xie et al. (2017) used MIKE URBAN to address multiple LID practices in a single watershed and calibrated the model using the water level at a pumping station forebay in the watershed to achieve R^2 ranging from 0.87-0.98.

1.3.3.8 MUSIC

MUSIC is widely used by urban catchment managers, primarily in Australia, as a model to evaluate alternative stormwater management including hydrology, water quality, and even economic aspects. The model includes bioretention as well as a range of other stormwater control measures, and is based on extensive field and laboratory studies (Wong et al., 2002). MUSIC uses continuous simulation, based on user-specified time step of between six minutes and 24 hours.

MUSIC has a large emphasis on water quality prediction as its probabilistic water quality analysis has obtained good results (eWater, 2013; Wong et al., 2006). The overland flow hydrology in MUSIC is adapted from Chiew and McMahon (1997) for smaller temporal scales. The bioretention hydrology is represented by a simple bucket model but it incorporates features specific to bioretention that could impact water quality such as effective versus non-effective vegetation and internal water storage zones.

There have been multiple calibration studies that have compared MUSIC to measured catchment runoff and water quality in catchments with bioretention or rain gardens (Gagrani et al., 2014; Hamel and Fletcher, 2014a; Hamel and Fletcher, 2014b; Imteaz et al., 2013). The model performed well for runoff at six minute to hourly intervals using multiple metrics such as the correlation coefficient (R^2=0.81 and R^2=0.82 for calibration and validation respectively by Gagrani et al. (2014) and Nash-Sutcliffe efficiency (NSE=0.59-0.64, Hamel and Fletcher (2014b); NSE=0.49-0.58, Hamel and Fletcher (2014a) ; NSE=0.49-0.81, Dotto et al. (2011)). However, water quality performance suffered in calibration studies (Imteaz et al., 2013; Dotto et al., 2011). Catchment scale studies have investigated model structure and sensitivity for watershed hydrology, but less focus has been given to individual bioretention cells (Hamel and Fletcher, 2014b; Burns et al., 2012; Dotto et al., 2011; Elliott et al., 2009).

1.3.3.9 RECARGA

RECARGA is a numerical model developed in MATLAB as a design tool to evaluate performance of bioretention cells, rain gardens, and infiltration trenches to meet design objectives or to understand flow behavior with varying design components (Atchison et al., 2006). The model reports total and hourly volumes for each water balance component over the continuous or single-event time period simulated. The first study to use RECARGA compared it to a similar model, RECHARGE, which used the Richards' equation for infiltration instead of the Green-Ampt method. RECARGA was found to produce runoff, recharge, and ponding depth results analogous to RECHARGE (Dussaillant et al., 2003). It has been used to size bioretention cells, investigate systems with and without underdrains, and evaluate effects of the bioretention to treatment area ratio on exfiltration into groundwater (Boancă et al., 2018; Gao et al., 2018; Montgomery et al., 2010; Turney and Neilson, 2010; Muthanna et al., 2007).

1.3.3.10 SWAT

The Soil-Water Assessment Tool (SWAT) was developed by the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS) to evaluate the effect of best management practices (BMPs) at a catchment scale. Although this model is a very detailed water balance model, it was developed for agricultural purposes and requires significant modification for urban applications such as adjustment for small catchments and small time-scales and updating ET and infiltration processes (Hunt et al., 2009). A study by Christianson (2003) used SWAT to model bioretention cells implicitly by considering bioretention cells as ponds. However, Christianson (2003) asserts that SWAT is not yet well-suited for urban applications. Jeong et al. (2010) described updated urban BMP algorithms in SWAT. These were used in a later study which reported lumped LID benefits including rain gardens at a watershed scale (Seo et al., 2017). SWAT has the potential to be beneficial for long-term catchment scale modeling of LID practices, but more research and modifications are needed.

1.3.3.11 SWMM

The U.S. EPA Stormwater Management Model (SWMM) has become one of the most widely used models for bioretention, especially since the release of SWMM5 which includes dedicated LID modules (Rossman, 2010). SWMM has many applications for catchment hydrology, provides several methods for hydrological and hydraulic processes and other input parameters, and reports outflow hydrographs and peak flows. Aad et al. (2010) was one of the first to model a rain garden (no underdrain present) with the SWMM LID module while Rosa et al. (2015) was the first to investigate calibration of LID catchments in SWMM. SWMM has been applied to bioretention in many case studies for LID watersheds (Avellaneda et al., 2017; Sun et al., 2014; McCutcheon and Wride, 2013; Bosley, 2008). SWMM has also been used to address specific design elements such as design storms, bioretention surface areas, soil mixtures and IWS zones (Lynn et al., 2018; Yang and Chui, 2018; Zhang et al., 2018b; Gulbaz and Kazezyilmaz-Alhan, 2017; Liu and Fassman-Beck, 2017). Lynn et al. (2018) compared the use of the bioretention LID module (added to SWMM5) with the traditional SWMM framework in the context of capabilities modeling the IWS zone. More recently, SWMM has been applied to groundwater interactions with bioretention cells (Kim et al., 2019; Zhang et al., 2018a). Other studies attempt to combine SWMM with other bioretention models such as HYDRUS-1D (Lynn et al., 2018), WinSLAMM (Tiveron et al., 2018), RECARGA (Sun et al., 2011) and HydroCAD (Lucas, 2010). Gulbaz and Kazezyilmaz-Alhan (2017) compare the model HM-RWB to SWMM and concluded that SWMM performed well compared to experimental drainage from column studies (R^2=0.66-0.76) but the HM-RWB performed better (R^2=0.77-0.85). These studies have proven that SWMM is capable of modeling bioretention cells although more studies are needed which focus on hydrologic behavior of individual bioretention cells through calibration and validation of SWMM to measured bioretention cell data.

1.4 Attributes of Advanced Hydrologic Modeling

In this section, attributes of hydrologic models that are beneficial for bioretention modeling are outlined. The simulation type, temporal scale, and spatial scale appropriate for bioretention applications are discussed. To be further considered as an advanced bioretention model, a model must meet these hydrologic modeling requirements. First, models must be continuous, long-term models with sub-hourly timesteps. Spatial scale is also evaluated but the benefits of site or catchment scale models depend on the application. Although many hydrologic/hydraulic models can meet these requirements, they must also have an explicit bioretention modeling component to be considered further in this review.

1.4.1 Simulation Type

Continuous versus event-based simulation is a common theme in hydrologic modeling. Event-based simulations provide analysis of natural or simulated storm events of various sizes. Continuous modeling uses a times series of precipitation data for simulation so that the timing of storms in relation to each other and to other modeled outputs can be assessed.

The biggest advantage of continuous modeling for bioretention cells is the ability to account for antecedent moisture content in the soil (Elliott and Trowsdale, 2007). Antecedent moisture content is an important parameter for considering variation in soil moisture in the bioretention cells which affects infiltration and storage capacity especially for small storms. Low initial moisture content (at the start of each storm) can lead to increased infiltration due to high soil suction while high initial moisture content can cause reduced infiltration and an increase in overflow. The largest disadvantages of continuous simulation are higher computational times and data requirements of a continuous rainfall record which are largely overcome by modern computing and data availability (Rossman and Huber, 2016b). Continuous simulations can be conducted by all process-based models evaluated except for HydroCAD.

Design storm analysis is beneficial in preliminary design analysis studies to understand how a system will respond to changes in storm intensity and duration. For example, the study which compared HM-RWB to SWMM-modeled bioretention cells evaluated a combination of storms with four different intensities and four different durations. This study found that in SWMM peak drain flowrates did not vary with respect to the rainfall duration and intensity although they did with HM-RWB (Gulbaz and Kazezyilmaz-Alhan, 2017). This shows that SWMM is not incorporating rainfall duration and intensity (unsteady flow) in calculating flow through bioretention cells but instead the bioretention function is dependent on soil and drainage properties. RECARGA, MOUSE/MIKE URBAN, MUSIC, and SWMM allow for continuous or single-event simulations depending on the user inputs. For single-event simulations, RECARGA requires the user to select from Soil Conservation Service (SCS) hyetographs and provide the 24-hour rainfall depth. MUSIC and SWMM allow a user to create a time-series for a natural or synthetic event.

1.4.2 Temporal Scale

Long-term simulations (>10 years) are beneficial for understanding a bioretention cell's response to various climate conditions and evaluating bioretention cell performance over its entire life cycle (Brown et al., 2013b). In all eleven process-based models reviewed, there is no limit on the length of simulation with user-defined continuous rainfall.

When considering long-term performance of bioretention cells, many design parameters could have seasonal variations such as soil and vegetative properties. However, for many models discussed in this paper, these parameters remain constant. Allowing for soil properties such as the saturated hydraulic conductivity or vegetation properties such as root and crop growth to be adjusted during the simulation could improve bioretention cell performance.

The time step used to evaluate model outputs can have a significant impact on the performance of the bioretention model. Models best suited for urban applications such as bioretention employ a sub-hourly time step. Lisenbee et al. (2020) demonstrated this point by recoding DRAINMOD to use time steps as small as one minute for inputs and outputs in DRAINMOD-Urban. When calibrating DRAINMOD-Urban to measured drainage hydrographs, good performance was achieved with NSE=0.60 at a 2-minute timestep. But, when the calibration to match measured volumes by Winston (2015) was used in DRAINMOD-Urban, the NSE was reduced to 0.31. The original DRAINMOD and SWAT were removed from further evaluation for not meeting the criteria of sub-hourly timesteps necessary for urban hydrologic applications.

RECARGA disaggregates hourly precipitation inputs into 15-minute time steps to calculate the runon to the bioretention cell, the soil moisture in each layer, the ponding depth, and the volumes for each component to the water balance but results are only printed on an hourly and total basis. MUSIC requires a user-specified time step of between six minutes and 24 hours. Six minutes is the minimum timestep in MUSIC because it corresponds with local precipitation records from the

Australian Bureau of Meteorology (eWater, 2013). RECARGA and MUSIC are the only continuous-simulation models discussed in this review with minimum time steps greater than one minute.

SWMM uses an adaptive time step that considers longer time steps in dry periods when systems are less dynamic and shorter time steps for wet periods when capturing changes in the system becomes more important. This process significantly reduces the total computational time as described for SWMM in the Hydrology Reference Manual (Rossman and Huber, 2016b). Similarly, DRAINMOD-Urban uses an hourly timestep during dry periods. GIFMod and HYDRUS use numerical solutions that employ time discretization based on the number of time steps needed for convergence which automatically adjusts the time step during the convergence process. The output time step can be determined by the user down to one minute.

1.4.3 Spatial Scale

Bioretention cells can be considered in a single site-scale model that focuses on the flow through the bioretention media and associated drainage, storage and exfiltration to surrounding soils. Bioretention cells can also be incorporated in a watershed model that allows users to visualize drainage areas that generate runoff for bioretention systems and route flows from bioretention cells to other elements downstream.

Site-scale models can incorporate user-defined inflow hydrographs calculated using another model such as SWMM for rainfall-runoff calculations in the drainage area. However, it is easier for both runoff generation and bioretention cell performance to be considered in the same model. Furthermore, watershed models often have good hydraulic processes to route hydrographs from one component to another. This incorporates time delays into runoff/inflow hydrographs. One downside of the site scale is the assumption that conveyance time of runoff from the drainage area to the bioretention cell is negligible (Atchison et al., 2006). This may be true when using models with time steps greater than the small time of concentration found in urban catchments, but when using models at very small time-steps, a delay could be seen in measured versus modeled hydrographs. Routing routines in watershed models also provide a means to model downstream effects of bioretention cells from drainage and overflow hydrographs.

While site-scale modeling is beneficial to evaluate effects of various design parameters or performance of a specific bioretention cell, watershed-scale modeling is more useful for planning purposes and broader ecosystem-level investigation. However, watershed-scale models for bioretention tend to lump parameters and make simplifications to allow for quick analysis of many contributing factors without cumbersome input requirements. To combine the best of these methods, it is suggested that site-scale models be incorporated as add-in tools for larger watershed models.

DRAINMOD-Urban and HYDRUS can only model the processes of a single bioretention cell without any built-in runoff generation procedures, instead relying on user-defined inflow. RECARGA can accept user-input inflow or can calculate runon from simple methods without any routing procedures. SWMM is a common watershed model applied to bioretention. This is because the LID modules allow the flow through the bioretention cell to be modeled as a separate subwatershed or as a part of an existing subwatershed. This allows flow to be routed to or from the bioretention cell using any of the routing procedures provided by SWMM. MUSIC is another catchment-scale model that uses an internal rainfall-runoff procedure developed by Chiew and McMahon (1997) to account for bioretention cell inflow and the Muskingum-Cunge routing algorithm between nodes. MOUSE/MIKE URBAN builds LID into existing MIKE URBAN catchments with the MOUSE kinematic wave runoff and routing procedures. GIFMod can model bioretention cells at the site-scale by considering each layer to be a separate connector block. GIFMod also allows the catchment area to be modeled as a single block in its block-connector model framework. Therefore, it can be connected to the bioretention cell and flow from one block to another can be simulated with several supplied equations.

1.4.4 Bioretention Modeling: Implicit or Explicit

As computational models for bioretention systems were developed, some authors explored using available hydrologic/hydraulic models and adapting the procedures in the model to fit bioretention processes. This implicit modeling was often confusing or cumbersome such as the method described by Lucas (2010) to model bioretention in HydroCAD. Other models were required to simplify the system to reservoir components such as in HEC-HMS (Heasom et al., 2006) or "soakaway" nodes in MIKE URBAN (DHI, 2017). Therefore, explicit functions for modeling bioretention cells were developed for many models such as the LID modules added to SWMM in 2010. However, some modelers prefer to use implicit storage functions to represent bioretention systems in SWMM depending on the application (Lynn et al., 2018). The models that explicitly model bioretention include DRAINMOD-Urban, GIFMod, HYDRUS, MOUSE/MIKE URBAN, MUSIC, RECARGA and SWMM.

1.5 Attributes of Advanced Bioretention Modeling

There are many approaches to modeling that can be applied to bioretention systems. Here we identify characteristics of models that are appropriate for advanced modeling of bioretention cell functions. First, a look at model inputs and outputs gives the user an idea of the complexity and applicability of the model. Next, specific bioretention attributes were evaluated: infiltration processes (Richards' equation; soil water retention), drainage configurations (underdrains; IWS), vegetation properties (ET; water uptake), and hydrograph production (Figure 1.3). These features are discussed further in the context of how they apply to separate components of the water balance in a bioretention cell. In the highest ranked models, DRAINMOD and SWAT have many attributes that are well-suited for bioretention modeling but did not meet the hydrologic modeling criteria of explicit bioretention functions or sub-hourly time steps (Figure 1.3). DRAINMOD-Urban is a revised version of DRAINMOD that considers urban hydrology for bioretention. This chart suggests that SWAT could also perform well as a bioretention model if it were also adapted to bioretention and urban systems. To further analyze bioretention functions, each model must have met at least four of the seven advanced bioretention modeling criteria (Figure 1.3). The six models that were further evaluated in this section as advanced bioretention models include: DRAINMOD-Urban, GIFMod, HYDRUS, MUSIC, RECARGA and SWMM.

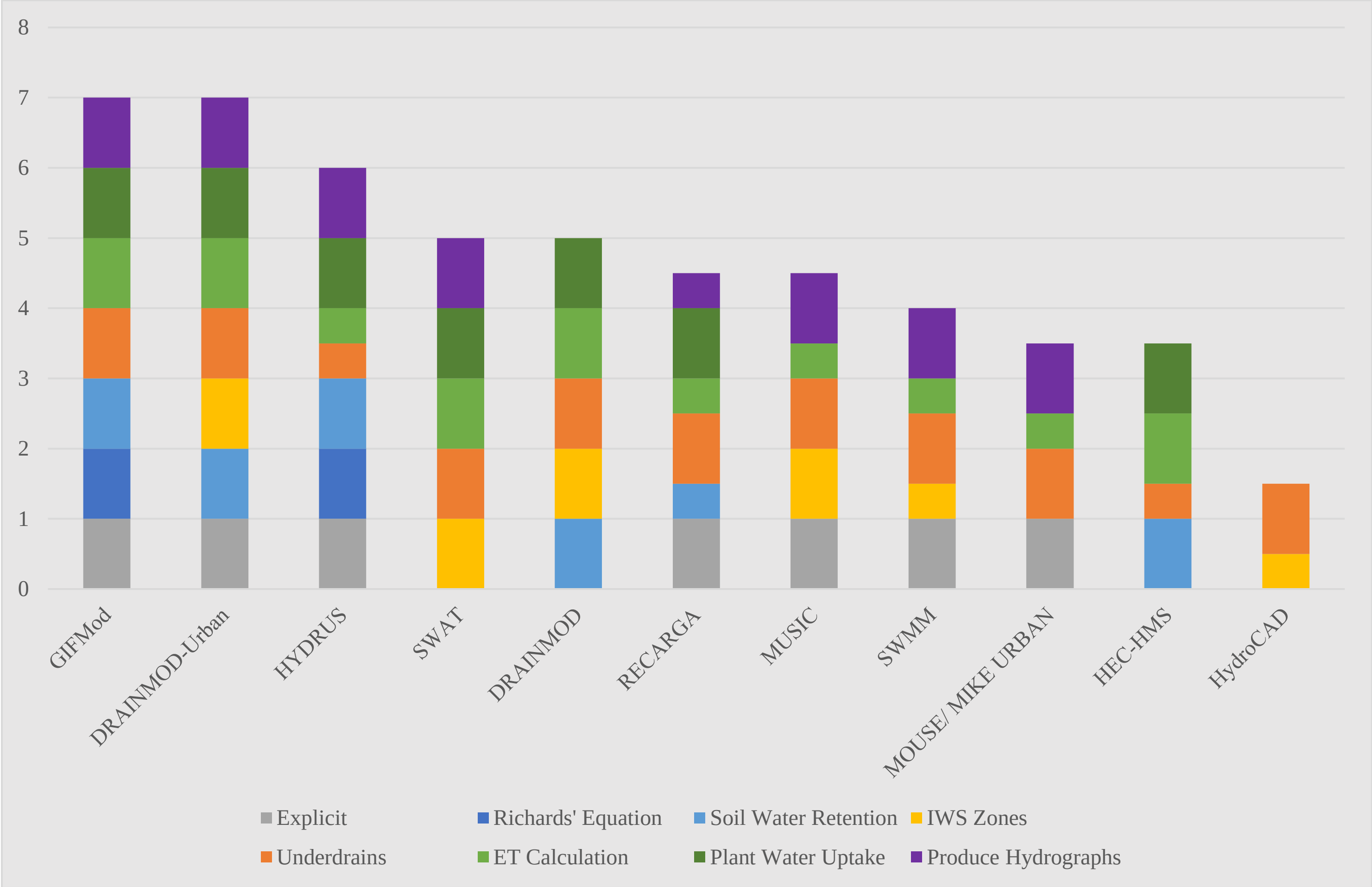

Figure 1.3. Advanced bioretention modeling attributes for all process-based models. Only those that could explicitly model bioretention and have at least four advanced bioretention attributes were considered further in this review. Bioretention attributes that have less capability than other models are represented by half-blocks.

1.5.1 Model Inputs

As the level of model complexity increases, so does the quantity and complexity of inputs. Table 1.3 shows the inputs required by each model. Inputs are broken into general categories: catchment properties, bioretention cell design, climate, soil, and vegetation parameters. An ideal model has a balance of intricate input parameters that require more time and effort from users and assumptions and simplifications in governing equations.

Modelers must be aware of the sensitivity of the model to certain parameters, particularly soil inputs, as well as the level of detail required for the modeling application. For example, Atchison et al. (2006) recommends performing infiltration tests on underlying soils for a detailed final design but for preliminary design applications, the soil hydraulic conductivity can be estimated based on soil texture. In RECARGA and SWMM, default values for soil properties based on soil texture from Rawls et al. (1998) are provided in the case that measured values are unavailable. Similarly, MUSIC provides estimations for soil inputs based on Melbourne and Brisbane soils (Imteaz et al., 2013).

All models require the Ksat and seepage rate as the most simplistic representation of inflow and outflow from the bioretention cell. Soil moisture properties are used in the infiltration and percolation equations to determine better estimations of the flow through the bioretention cell. The SWCC is the best characterization of soil moisture changes because it provides an iterative curve of soil moisture with respect to soil suction. However, only the models that use Richard's equation (GIFMod and HYDRUS) and DRAINMOD-Urban use this method for soil-water accounting. Other models that use Green-Ampt infiltration require the initial soil moisture and other common soil moisture properties such as porosity, field capacity, and wilting point. These values are often based on soil texture as mentioned above. RECARGA, HYDRUS and GIFMod offer soil parameter estimation for the unsaturated hydraulic conductivity function $K(\Theta)$ from the van Genutchen equation. HYDRUS also offers Brooks-Corey, Kosugi, and a modified van Genuchten function as options for soil-moisture accounting. GIFMod calculates soil properties and flow through various block types (saturated soil, unsaturated soil, storage, etc.) with two pre-defined soil-water relationships: head-storage and head-flow functions.

1.5.2 Model Outputs

All models reviewed produced hydrographs and summary reports of cumulative volumes for each water balance component in the bioretention cell. SWMM and MUSIC provide flow statistics such as minimum, maximum, mean, standard deviation, etc. SWMM also includes an LID performance summary (cumulative) and detailed LID report (at each time step) that accounts for water balance volumes specifically within the LID control. Another advantage of SWMM is that hydrographs can be easily viewed in the user interface. This is also true for GIFMod, MUSIC, and HYDRUS whereas DRAINMOD-Urban and RECARGA provide outputs in the form of text files. HYDRUS, MUSIC, and SWMM also describe characteristics of the hydrographs such as time to peak, peak flow rate, and duration in the result summaries. These hydrograph characteristics can be found in time series outputs from DRAINMOD-Urban and GIFMod. Although hourly flows in RECARGA can still be used to create hydrographs, it may not accurately capture peak flows.

HYDRUS, MUSIC, and RECARGA verify the accuracy of reported results by also calculating mass balances on the water fluxes. Soil moisture in various layers of the bioretention cell is reported for GIFMod and RECARGA and an average of the soil moisture in the soil layer is reported in SWMM at each time step. Similarly, the depth of the water table in the bioretention cell is reported at a 1-minute interval in DRAINMOD-Urban. This is useful for comparison to water levels measured with a well and water-level logger such as in Brown et al. (2013b). The RECARGA synopsis of plant survivability output details each time the rooting zone is saturated or permanent wilting point is reached, each time there is ponding, and each overflow event. RECARGA also has the capability of determining a facility [bioretention] area ratio (FAR) to meet a given "stay-on" target meaning the amount of water remaining in the cell (precipitation minus overflow and drainage). Similarly, HYDRUS reports "water retained" and SWMM reports the initial and final storage as a "stay-on" output.

Table 1.3. Input and output components of all evaluated models: Dark blue boxes indicate an input feature required in the model and output capabilities; Light blue boxes indicate an optional input feature.

		Model Name:	**DRAINMOD-Urban**	**GIF-Mod**	**HYDRUS**	**MUSIC**	**RECARGA**	**SWMM**
Catchment Properties	Geometry	Catchment Area						
		Catchment Width						
	Land Cover	% Imperviousness						
		Pervious CN						
		Impervious Manning's n						
		Pervious Manning's n						
		Depression Storage						
		% of Area w/o Depression Storage						
	Runoff	User-defined Inflow						
BRC Design Properties	Geometry	BRC Area						
		BRC Area: Catchment Area Ratio						
		BRC Width						
	Ponding Layer	Ponding Layer Depth						
		Initial Ponding Depth						
		Overflow Weir Coefficient						
	Drainage	Underdrain Diameter						
		Underdrain Flow Coefficient						
		Underdrain Flow Exponent						
		Underdrain Offset Height						
		Drain Spacing						
		IWS Depth						
	BRC Media	BRC Media Depth						
		BRC Surface Roughness (Manning's)						
		Unlined BRC Media Perimeter						
		Initial Water Table Depth						

Table 1.3 (continued). Input and output components of all evaluated models: Dark blue boxes indicate an input feature required in the model and output capabilities; Light blue boxes indicate an optional input feature.

		Model Name:	DRAINMOD-Urban	GIF-Mod	HYDRUS	MUSIC	RECARGA	SWMM
BRC Design Properties	Storage Layer	Storage Layer Depth						
		Storage Void Ratio						
		Piezometric Head						
		Thickness of Restricting Layer						
		Seepage Rate						
Climate		Precipitation						
		Temperature						
		Humidity						
		Wind						
		User-input PET						
Soil	BRC Media	Soil Texture						
		Porosity						
		Bulk Density						
		Initial Moisture Content						
		Residual Moisture Content						
		Field Capacity Moisture Content						
		Wilting Point Moisture Content						
		Suction Head						
	Hydraulic Conductivity (HC)	Saturated HC of Layers						
		Unsaturated HC of Layers						
		HC Slope (HCO)						
	Soil Flow Functions	Soil-Water Characteristic Curve						
		Head-Storage Relationship						
		Head-Flow Relationship						

Table 1.3 (continued). Input and output components of all evaluated models: Dark blue boxes indicate an input feature required in the model and output capabilities; Light blue boxes indicate an optional input feature.

		Model Name:	**DRAINMOD-Urban**	**GIF-Mod**	**HYDRUS**	**MUSIC**	**RECARGA**	**SWMM**
Vegetation		Root Layer Depth						
		Vegetation Volume Fraction						
		Unvegetated						
		Effective Nutrient Removal?						
Outputs		Reports total volumes						
		Reports peak flows						
		Produces hydrographs						
		Data visualization in user interface						
		Routing to other watersheds/components						
		Mass balances for verification						

1.5.3 Water Balance Components

Modeling the water balance of a bioretention cell describes its performance with respect to various design parameters. For example, too many overflow events could indicate that a larger ponding depth is required or that more storage volume in the bioretention media is needed. Conversely, very few overflow events could indicate that the cell was oversized or that surrounding soils have high infiltration rates (often the limiting factor). Therefore, how each water balance component is represented in a model can drastically change the modeled bioretention cell behavior and, more importantly, the design recommended for given conditions. Each model provides its own representation of bioretention processes and it is apparent that although they are all modeling the same flow paths, there are many possible approaches. Furthermore, modelers determine suitable models based on the governing equations used to calculate flow in each component of the water balance (Table 1.4).

Table 1.4. Processes in advanced bioretention cell models as related to each water balance component. Some fields were evaluated based on the varying model aptitude (H=High, M=Medium, and L=low).

		DRAINMOD-Urban	***GIF-Mod***	***HYDRUS***	***MUSIC***	***RECARGA***	***SWMM***
Inflow	*Runoff Generation*	user-input	user-input	user-input	simplified rainfall-runoff model developed by Chiew and McMahon (1997)	SCS CN & initial abstraction, user-input	SCS CN, Rational method, Unit hydrograph, user-input
	Flow Routing	n/a	Diffusive Wave/Manning; Darcy's law; Rating curve; Pipe: Hazen-Williams	Dynamic wave	Muskingum Cunge; simple lag time	n/a	Steady flow, Kinematic wave, Dynamic wave; Pipe: Hazen-Williams, Darcy-Weisbach, Manning (free surface)
Infiltration	*Surface Infiltration*	Green-Ampt	Richards' Equation	Richards' Equation	Simple bucket model	Modified Green-Ampt	Modified Green-Ampt
	Infiltration between layers	Green-Ampt	Van Genuchten-Mualem (unsaturated); Darcy (saturated)	Van Genuchten-Mualem; modified Van Genuchten; Brooks-Corey; Kosugi	Exponential equation of Ksat	K(Θ) from Van Genuchten	Darcy's law using HCO parameter to describe slope of K(Θ)
	Accounts for Soil Water Retention	H	M	M	n/a	M	n/a

*HCO=Hydraulic conductivity slope which is the slope of the curve of log(unsaturated conductivity) versus soil moisture content (Rossman and Huber, 2016a).

Table 1.4 (continued). Processes in advanced bioretention cell models as related to each water balance component. Some fields were evaluated based on the varying model aptitude (H=High, M=Medium, and L=low).

		DRAINMOD-Urban	*GIF-Mod*	*HYDRUS*	*MUSIC*	*RECARGA*	*SWMM*
Outflow	*IWS Zones*	H	n/a	n/a	M	n/a	L
	Underdrains	H	H	L	M	M	M
	Drainage Equation	Hooghoudt Equation or Kirkham Equation	Hazen-Williams Equation	Tile drain boundary condition	Orifice equation	Orifice equation	Weir or Orifice equation
Overflow	*Ponding Depth*	Ponding>Max Ponding Depth	Constant head-storage relationship	Seepage face boundary condition	Weir equation	Ponding>Max Ponding Depth	Ponding>Max Ponding Depth
Exfiltration	*Seepage Equation*	Darcy's law and Dupuit-Forchheimer assumptions	Darcy's law	Van Genuchten-Mualem, modified Van Genuchten, Brooks-Corey, Kosugi	Ksat of surrounding soil	Van Genuchten	Ksat of surrounding soil
Evapo-transpiration	*PET Calculation*	Thornthwaite, user-input	Aerodynamic model, Preiestly-Taylor, Penman, transpiration models, user-input	Atmospheric boundary conditions	user-input	user-input	user-input
	Plant Water Uptake	Water level in root zone using SWCC	FAO-56 or Li et al., 2001	Feddes et al. (1978) or van Genuchten (1985)	Water level in soil layer	Soil moisture in root zone	Water level in soil layer
	Root Depth	H	n/a	H	L	H	n/a

1.5.3.1 Inflow

DRAINMOD-Urban and HYDRUS rely solely on user-input inflow, but in previous studies, SWMM was used to provide a 1-minute inflow hydrograph using the Green-Ampt method (Lisenbee et al., 2020). Similarly, runoff generation from the drainage area could be calculated with any rainfall/runoff method giving the users more flexibility.

MUSIC has a built-in model for rainfall-runoff prediction based on the study by Chiew and McMahon (1997). RECARGA offers a built-in process for producing hourly inflow calculated with the SCS Curve Number (CN) method for pervious sections and an initial abstraction method for impervious sections but can also use user-defined inflow. Similarly, GIFMod can accept user-specified inflow or calculate runoff from a separate block that is directed into the bioretention cell as inflow.

SWMM offers the most comprehensive methods for runoff generation. Its default method is a nonlinear reservoir model that incorporates Manning's equation for overland flow and accounts for depression storage. Alternative methods include Rational Method, SCS CN method, unit hydrograph method from Natural Resource Conservation Service (NRCS) and user-input values. SWMM also can account for directly connected impervious areas to distinguish effective imperviousness separate from the total imperviousness. This distinction is important is urban hydrologic modeling to improve runoff estimation.

For watershed models, flow routing can be considered between components using the steady flow, kinematic wave, and dynamic wave methods in SWMM and the diffusive wave/Manning's technique in GIFMod. This capability is useful for investigating effects of bioretention cells on downstream BMPs or control features (Heasom et al., 2006). One example is modeling treatment trains that link many LID practices in series. MUSIC is often used for treatment train applications using the Muskingum-Cunge routing procedures between each stormwater control measure (eWater, 2013). Another application is linking bioretention cells to sewer systems particularly for studying mitigation of CSOs (Lucas, 2010).

1.5.3.2 Infiltration

Although Richards' equation is widely considered the most comprehensive infiltration model, it requires the unsaturated hydraulic conductivity curve, K(Θ), and the soil water characteristic curve (SWCC) which are two soil properties that are not easily measured. Therefore, the Green-Ampt equation, a simplification of the Richards' equation, is used in many models to reduce input requirements and computation demand. These simplifications require certain assumptions of the Green-Ampt method such as one-dimensional, vertical flow and total saturation behind a sharp wetting front. These assumptions are not always valid in bioretention cells which operate under variably saturated and unsaturated conditions.

HYDRUS, which was developed as a soil physics model, uses Richards' equation. A collection of equations (Van Genuchten-Mualem, modified Van Genuchten, Brooks-Corey, and Kosugi) are proposed to estimate the K(Θ) required in Richards' equation. To populate these equations, the soil routine ROSETTA was used to determine the water retention parameters used in the van Genuchten flow equations from easily determined soil textures.

GIFMod also offers a suite of relationships to describe interactions between blocks that represent different soil or storage components. Infiltration can only be calculated with Richards' equation which is the most comprehensive method but requires complex inputs. Then percolation through subsurface layers is estimated by the van Genuchten-Mualem unsaturated hydraulic conductivity or Darcy flow in saturated conditions.

DRAINMOD-Urban uses this Green-Ampt approximation of Richards' equation for infiltration through all bioretention cell layers but utilizes a user-defined SWCC to account for soil moisture changes in a bioretention cell, especially those with an IWS zone when the water table is close to the surface. Brown et al. (2013b) emphasized the importance of the soil moisture changes with respect to the internal water level by comparing the water content using the SWCC to more common methods of assuming the difference between saturation and field capacity. This study highlighted extremely large percent differences of water content (-6017 to -14%), as the water level rose closer to the surface. Therefore, the SWCC is a better parameter to use in determining infiltration through bioretention systems since the water level is often near the surface.

RECARGA uses the Green-Ampt equation with ponding for infiltration of runoff into the soil surface. Then, the unsaturated hydraulic conductivity calculated with the van Genuchten equation determines the flow through each of the three soil layers: root zone, storage zone and native soil zone. If the underlying layer is saturated, the model corrects the infiltration/drainage by using the limiting hydraulic conductivity plus underdrain flow if present. A model, RECHARGE, similar to the RECARGA model but using Richards' equation, was shown to have comparable recharge (exfiltration) to RECARGA under varying design parameters indicating that Green-Ampt can still approximate infiltration to a sufficient level (Dussaillant et al., 2003).

SWMM offers a wide variety infiltration options in subcatchments (Horton's method, the Green-Ampt method, and the SCS CN method) but for the LID module, a modified Green-Ampt is used. It was adjusted to account for ponding depth which is normally ignored in the Green-Ampt equation but is relevant to bioretention infiltration. SWMM uses Darcy's law to simulate percolation through subsequent soil layers in the bioretention cell. This is applied in the same manner as SWMM's groundwater routine using the hydraulic conductivity coefficient (HCO) to describe the exponential decrease in hydraulic conductivity with decreasing moisture content (Rossman and Huber, 2016a). This HCO parameter is generally estimated based on soil texture but guidance in SWMM suggests a range much larger than the HCO used in other bioretention studies (Lynn et al., 2018; Liu and Fassman-Beck, 2017). Instead of using a soil-accounting method like DRAINMOD-Urban, SWMM assumes all soil moisture is evenly distributed throughout the soil layer and soil matric forces are ignored such that the entire system acts as a simple storage reservoir (Rossman and Huber, 2016a).

Lastly, MUSIC uses a simple bucket model to develop infiltration equations based on the total available volume in each layer and a mass balance of the fluxes within a bioretention cell. The infiltration from the ponded zone into the soil layer is the minimum of the available water (inflow + ponded water – overflow), potential infiltration (the volume of water leaving the soil layer), and soil capacity (the volume available in the soil at a given moisture content). The infiltration rate within the soil media is simply the change in moisture content times the soil capacity (total volume of the soil media times the porosity). To consider the fluxes to other components of the bioretention cell, the ET and seepage to the storage layer are subtracted from this infiltration rate.

1.5.3.3 Outflow

Two important considerations for modeled outflow are underdrain configurations and IWS zones. The inclusion of these features comes in many forms. GIFMod models underdrain flow as simple pipe flow from the storage layer using the Hazen-Williams equation. HYDRUS models the underdrain as its own highly permeable soil layer that is constrained by a tile drainage boundary condition. Although RECARGA has the ability to calculate underdrain flow with an orifice equation, the underdrain can only be placed between the root zone and storage zone. This configuration does not allow for an IWS zone using an upturned elbow in the underdrain nor does it accommodate other restrictions to the underdrain such as valves, orifice plates, weirs, etc.

MUSIC allows users to click a checkbox to indicate use of an underdrain and if present, an IWS zone. For an underdrain, MUSIC calculates drainage using an orifice equation when the water level in the bioretention cell is greater than the height of the drainpipe. Similarly, drainage with an IWS zone is only calculated when the internal water level is above the invert of the elbow outlet.

SWMM includes underdrains as an optional function in the bioretention cell LID control editor. SWMM models flow through the underdrain with a simple empirical power law weir equation unless the maximum drainage limit is reached. The user defines the offset height of the underdrain to allow for a storage layer underneath the pipe. Although IWS zones cannot be modeled in the LID module, a recent study suggested a method of using the traditional SWMM framework to model a bioretention cell with an IWS zone (Lynn et al., 2018). SWMM does consider other restrictions on flow with orifice or weir equations defined by the drainage coefficient and drainage exponent set by the user.

Because the original DRAINMOD was developed as an agricultural drainage model, DRAINMOD-Urban is one of the best models for both underdrains and IWS configurations. DRAINMOD-Urban uses the Hooghoudt drainage equation when the internal water table is below the surface and corrects for convergence of flow near the drains using the Moody equations. When the soil profile is saturated and there is ponding on the soil surface, the Kirkham equation is used to calculate the drainage rate. DRAINMOD-Urban is the only model that, by default, models multiple drainage pipes. It also provides a drainage coefficient for flow limited by pipes or outlet structures. DRAINMOD-Urban provides a "controlled drainage" design option that has been shown to accurately model drawdown (as DRAINMOD) in a bioretention cell with an IWS zone during the growing season but during the dormant season (when water tables rise due to reduced ET) drawdown was slower than predicted rates (Brown et al., 2013b). This is one of few studies that has evaluated the model performance for an IWS zone.

1.5.3.4 Overflow

In general, all models predict overflow when the ponding depth exceeds the depression storage depth. DRAINMOD-Urban, RECARGA, and SWMM use a simple surface water balance to account for change in storage of the ponding zone. DRAINMOD-Urban specifically uses the SWCC to recalculate the water level in the cell at each time step and determine if the maximum ponding depth has been reached. SWMM includes a ponding zone (denoted berm height) in the LID module for bioretention but also includes a vegetation volume fraction to account for the space that vegetation occupies in the ponding zone. Overflow, when the ponding zone is full, is modeled with a surface layer water balance as the precipitation and inflow minus infiltration and evapotranspiration at the surface. This is calculated in the model as the water level above a maximum freeboard for each given timestep.

HYDRUS uses a seepage face boundary condition to model water leaving the saturated zone as overland flow. In GIFMod, the ponding zone is modeled as a separate block with a constant head-storage relationship. Runoff from the ponding zone can then be routed to another block as overland flow. MUSIC uses a simple weir equation to describe flow from the ponding zone after reaching the designated berm height.

1.5.3.5 Exfiltration

In RECARGA, the underlying soil is considered as an additional soil layer such that exfiltration is quantified in the water balance at each time step using the unsaturated hydraulic conductivity calculated with the van Genuchten equation. HYDRUS also uses the unsaturated hydraulic conductivity from the Van Genuchten-Mualem, modified Van

Genuchten, Brooks-Corey, or Kosugi methods to govern seepage into the surrounding soils.

DRAINMOD-Urban uses a vertical seepage function that incorporates Darcy's law with the Dupuit-Forchheimer assumptions to describe the flow from the storage layer into the surrounding soil. The model inputs include seepage parameters such as piezometric head of the aquifer, depth to the impermeable layer, and vertical conductivity of the restricting layer which are often used as calibration parameters since they are difficult to measure. Likewise, Darcy's law is used in GIFMod to simulate flow from the bioretention media into the gravel layer and subsequent native soils. In SWMM and MUSIC, the exfiltration from the bottom of the storage layer into the surrounding native soil is simply set to a user-supplied saturated hydraulic conductivity of the native soil.

1.5.3.6 Evapotranspiration

Evapotranspiration (ET) is difficult to model and the most accurate equations require a large number measured meteorological parameters; consequently, methods employed in bioretention models vary widely. Studies have shown ET makes up approximately 5-20% of the bioretention cell water balance with higher ET found in bioretention cells with an IWS zone (Winston et al., 2016; Wadzuk et al., 2015; Brown et al., 2013b; Li et al., 2009). However, understanding ET dynamics in bioretention cells is important since vegetation is incorporated specifically for increased water storage and removal (in addition to water quality benefits).

In RECARGA, the regional average hourly ET was used to calculate the available initial abstraction in the impervious surface runoff. For the bioretention cell itself, a function of the user-input hourly potential evapotranspiration (PET) and the plant available water was used to calculate ET from the rooting zone. RECARGA outputs a synopsis of plant survivability which includes details for each time the rooting zone is saturated or permanent wilting point is reached, each time there is ponding, and each overflow event. The ponding time is included because plant survivability is expected to decrease if ponded over 24 hours (Atchison et al., 2006).

SWMM has many methods (constant value, monthly averages, daily values from external climate file, daily values computed from daily temperatures, and daily user-defined times series) available to calculate evaporation for overland flow where plant transpiration is negligible. Surface ET in the LID module is calculated by incorporating a user-defined daily PET input and ponding depth over time into a function for the evaporation from the surface. In the soil layer, the minimum of the remaining PET and the ET calculated by a function of moisture content above wilting point and the water level. The ET can also be calculated for the storage layer when the soil layer is unsaturated. Both the soil and storage ET are set to zero when surface infiltration is occurring.

Similarly, MUSIC calculates the ET at a daily time step from the surface and soil layers separately. The evaporation at the surface is calculated without considering transpiration from plants. This is added to the ET from the soil layers which is dependent on soil moisture and water availability. When the soil moisture is above wilting point, but vegetation still experiences water stress, the PET is limited by water availability. If the water availability is not limiting, the ET is set equal to the PET. These ET equations were based off a column study using the *Carex Appressa* plant (commonly used in bioretention systems in Australia). In MUSIC, plant survivability is considered in relation to the IWS zone and nutrient uptake for water quality. Vegetation is considered to be effective or non-effective vegetation in relation to nutrient uptake which is commonly associated with root depth (eWater, 2013).

In DRAINMOD-Urban, the Thornthwaite method is the default ET method due to its simple input requirements: daily maximum and minimum temperatures, heat index and latitude. Monthly adjustment factors can also be applied to better calibrate the ET to a specific region. Additionally, a user-defined daily PET can be entered to allow flexibility in the PET calculation method. Daily ET is distributed between 6:00 and 18:00 and PET is set to zero during rainfall. ET occurs in the root zone which is an input parameter for DRAINMOD-Urban that can be adjusted monthly to account for seasonality. In DRAINMOD-Urban, the PET is used to represent the ET from the system when the soil water is not limiting. If the ET is limited by the soil water conditions such as when the soil moisture in the root zone is below the permanent wilting point, then ET is equal to the upward flux of water as a function of the water table depth (which is determined from the SWCC soil input). When this upward flux is not enough to meet the ET demand, water is removed from the root zone.

GIFMod has the largest number of programmed options for calculating PET within the model including an aerodynamic model for evaporation, Priestly-Taylor, Penman and user-defined methods (Massoudieh et al., 2017). GIFMod also has two transpiration models that limit transpiration either by soil moisture or soil matric potential. The water uptake from plants can be modeled with the FAO-56 model or another model that considers field capacity, wilting point and soil suction proposed by Li et al. (2001).

HYDRUS uses atmospheric boundary conditions to account for release of water through evaporation in the ponding zone. The water uptake can be described as function of a critical water stress above which the water uptake in stressed parts of the root zone can be compensated by uptake in other parts of the root zone. To find the actual rate of water uptake, a water stress response function by Feddes et al. (1978) or van Genuchten (1985) can be used to reduce the potential root water uptake. Water uptake is assumed to be zero when the soil is saturated and when it is below wilting point. In HYDRUS, maximum rooting depth is entered by the user and in HYDRUS 2D/3D, the maximum rooting radius is used to consider lateral spread of roots (Šejna et al., 2014). HYDRUS also accounts for plant growth in ET calculations using the plant height and root depth. Meng et al. (2014) found that ET volume increased with plant height.

1.6 Assessment of Needs for Bioretention Modeling

This review unveiled a number of improvements to bioretention modeling to be considered in future modeling efforts. Few models account for aboveground vegetation growth and root growth which can increase ET. HYDRUS is the only model evaluated that includes plant growth in its ET calculation. The only other model that acknowledges aboveground effect of plants is SWMM which accounts for the space plants take up in the ponding zone with its vegetation volume fraction. However, this is a constant rate that does not account for plant growth over the simulation period. The rooting depth of plants is incorporated in many models' water uptake procedures, but this is also often a constant value. Only HYDRUS accounts for root growth both longitudinally and laterally. DRAINMOD-Urban can incorporate seasonal root growth with monthly rooting depths but this is repeated for each year in the simulation so that growth from one year to the next is overlooked.

Many studies have shown effects of vegetation on infiltration through creation of macropores (Meng et al., 2014; Lucas, 2010; Atchison et al., 2006). Vegetation can lead to infiltration rates several orders of magnitude higher than predicted solely by associated soil properties (Lucas, 2010). Meng et al. (2014) notes that although HYDRUS incorporates plant growth in the model, there is no ability to simulate the effect of plants on soil permeability due to macropores. While macropores increase infiltration, clogging of soil pore space due to fine particle accumulation can decrease infiltration. SWMM is the only model that accounts for clogging with a user-specified constant clogging rate. Infiltration parameters also been shown to vary seasonally due to plant growth or dormancy, temperature changes, and snow events (Emerson and Traver, 2008; Muthanna et al., 2008; Braga et al., 2007). Despite this evidence, none of the models allow for temporal variation of the K_{sat} and other soil properties.

Soil properties play an important role in the soil moisture dynamics of bioretention cells which affects the infiltration, percolation, and other hydrologic flow paths. DRAINMOD-Urban, GIFMod, and HYDRUS require the SWCC which provides information on soil moisture properties of the bioretention media. Other models suggest estimations of soil moisture properties such as porosity, field capacity and wilting point based on soil texture from experimental studies such as Rawls et al. (1998) used in RECARGA or Rawls et al. (1983) used in SWMM. However, even measured soil attributes have large variability even across similar soil textures due to land cover, compaction, macropores, temperature, etc. Saturated hydraulic conductivity has been shown to vary widely up to three orders of magnitude with associated high skewness from various studies (Garcia-Gutierrez et al., 2018; Papanicolaou et al., 2015; Gwenzi et al., 2011; Warrick and Nielsen, 1980). Further study default values for a given soil textural class and measured values of soil properties in bioretention modeling would provide valuable information on model sensitivity to soil parameters.

Both IWS zones and underdrains are oversimplified and underrepresented in most of the models evaluated. Underdrains are commonly applied in bioretention field studies, and some states require IWS zones for bioretention (North Carolina Department of Enviromental Quality, 2009; Ohio Department of Natural Resources, 2006). These configurations must be included in modeling approaches in order for the model to adequately represent the bioretention hydraulics. Also, most models had simplistic drainage equations and only considered a single underdrain. DRAINMOD-Urban is the only model that accounts for multiple drains using drainage equations applied to poorly-drained agricultural soils.

Exfiltration from the bioretention cell to native soils can be improved in some models that assume a constant rate such as the saturated hydraulic conductivity. Darcy's law is an improvement in some models but considering unsaturated flow is even more advanced. Also, a benefit of the IWS zone is to increase the exfiltration into surrounding soils by slowing the flow of water through the underdrain. Most models are incapable of modeling IWS zones and therefore, may overestimate drainage and underestimate exfiltration.

More studies need to be conducted using measured field data for calibration and validation of these models. Many studies use these models as planning tools, but model performance must be validated with field studies to assure that uncalibrated model simulations provide realistic estimations for preliminary designs. Furthermore, models that assess lumped bioretention outflows at the catchment scale could show good performance of total runoff reduction but if flow dynamics is important to the modeling application, outflow hydrographs from individual bioretention cells must also be calibrated.

A few models have shown limited capabilities regarding bioretention influence on groundwater indicating this as another area that can be investigated further. Some studies have tried to adapt models like HydroCAD and SWMM to account for groundwater recharge and other assume all exfiltration becomes recharge but there is still much to learn about the effects of bioretention and other infiltration devices on groundwater to inform models (Bonneau et al., 2018; Zhang and Chui, 2018; Zhang et al., 2018a; Stewart et al., 2017; Zhang and Chui, 2017; Machusick et al., 2011; Barbu et al., 2009). Many models fail to account for the changing hydraulic gradient of the groundwater table and how it affects the seepage rate from the bioretention cell. Of the models in this paper, DRAINMOD-Urban and HYDRUS have these capabilities.

Water quality features of the models in this review were not evaluated but the assessment of model hydrology is a step toward improved water quality predictions. Improved modeling of bioretention cell hydrology can lead to improvement in water quality pollutant loadings. The contaminant transport, nutrient transformation, and biological activity within bioretention cells are important to the quality of water reaching downstream catchments and other LID controls but often these are secondary to load reductions from a decrease in runoff volumes. Nevertheless, investigation into the water quality processes of bioretention models is an area for further research.

1.7 Conclusions

This review served to unveil the black box of hydrologic processes in common bioretention models and identify improvements in the field of bioretention modeling. Two relatively new models were among the models analyzed: DRAINMOD-Urban (2020) and GIFMod (2017). Conversely, SWMM, MUSIC, and RECARGA have been used in many studies. HYDRUS has been used in fewer studies perhaps due to model complexity. All of these models meet the first three attributes for advanced modeling: continuous simulation, sub-hourly time steps (as small as 1-minute time steps available in all models except RECARGA and MUSIC), unlimited simulation duration. Spatial distribution of the models varies: both catchment models and site-scale models are represented. Downsides of the site scale are neglecting conveyance time of runoff from the drainage area to the bioretention cell and inability to route outflows to other catchments, sewer systems, or LID components downstream.

Richards' equation is suggested as the most advanced physical representation of infiltration through the bioretention cell, but it is only used in HYDRUS and GIFMod due to difficulty obtaining required input parameters. A simplification of Richards' equation, Green-Ampt, is used by other models but it makes assumptions that are not always applicable to the variably saturated nature of bioretention cells. Therefore, modified Green-Ampt equations have been used in models such as SWMM and RECARGA that account for the ponding depth. DRAINMOD-Urban uses Green-Ampt but also accounts for variable moisture content in the cell through use of the SWCC. GIFMod, HYDRUS and RECARGA use the van Genuchten approximation for the unsaturated hydraulic conductivity to account for percolation through the subsoil layers. Despite meticulous percolation procedures, these three models still lack the ability to model IWS zones in a typical upturned elbow configuration, with HYDRUS and RECARGA even more limited in underdrain configurations. DRAINMOD-Urban is the most comprehensive drainage model, and therefore, models both IWS and underdrain components well. MUSIC also explicitly models both underdrains and IWS zones.

Some improvements suggested for bioretention modeling based on this review are incorporation of vegetation growth and root growth over time, temporal variation of soil properties, the validity of soil parameters estimation, and customization of drainage configurations. Groundwater and water quality analysis are two important topics of investigation with regard to bioretention that were not covered in this review, but research is ongoing. Further calibration and validation of the models with measured field data will improve confidence in model performance for bioretention applications.

Catchment-scale models must be evaluated on how they represent individual bioretention cells to understand how the flow dynamics will interact with other watershed components. These improvements in process-based bioretention modeling will lead to better prediction of bioretention behavior.

1.8 REFERENCES

Aad, M.P.A., Suidan, M.T. and Shuster, W.D. (2010) Modeling Techniques of Best Management Practices: Rain Barrels and Rain Gardens Using Epa Swmm-5. Journal of Hydrologic Engineering 15(6), 434-443. https://doi.org/10.1061/(Asce)He.1943-5584.0000136

Akan, A.O. (2013) Preliminary Design Aid for Bioretention Filters. Journal of Hydrologic Engineering 18(3), 318-323. https://doi.org/10.1061/(asce)he.1943-5584.0000554

Al-Ameri, M., Hatt, B., Le Coustumer, S., Fletcher, T., Payne, E. and Deletic, A. (2018) Accumulation of Heavy Metals in Stormwater Bioretention Media: A Field Study of Temporal and Spatial Variation. Journal of Hydrology 567, 721-731. https://doi.org/10.1016/j.jhydrol.2018.03.027

Alexander, M.D., Barfield, B.J., Hayes, J.C., Harp, S.L., Chalavadi, M., Yeri, S., Stevens, E. and Bates, B.T. (2011) Modeling Low Impact Development Water Quality Bmps with Ideal. Beighley II, R.E. and Killgore, M.W. (eds), American Society of Civil Engineers, Palm Springs, CA.

Asleson, B.C., Nestingen, R.S., Gulliver, J.S., Hozalski, R.M. and Nieber, J.L. (2009) Performance Assessment of Rain Gardens(1). Journal of the American Water Resources Association 45(4), 1019-1031. https://doi.org/10.1111/j.1752-1688.2009.00344.x

Atchison, D., Potter, K. and Severson, L. (2006) Design Guidelines for Stormwater Bioretention Facilities. White, E. and Wittman, S. (eds), Water Resources Institute, University of Wisconsin.

Avellaneda, P.M., Jefferson, A.J., Grieser, J.M. and Bush, S.A. (2017) Simulation of the Cumulative Hydrological Response to Green Infrastructure. Water Resources Research 53(4), 3087-3101. https://doi.org/10.1002/2016wr019836

Barbu, I.A. and Ballestero, T.P. (2015) Unsaturated Flow Functions for Filter Media Used in Low-Impact Development—Stormwater Management Systems. Journal of Irrigation and Drainage Engineering 141(1), 04014041. https://doi.org/10.1061/(asce)ir.1943-4774.0000766

Barbu, I.A., Ballestero, T.P. and Roseen, R.M. (2009) Lid-Swm Practices as a Means of Resilience to Climate Change and Its Effects on Groundwater Recharge. Steve Starrett, P.D., P.E. (ed), ASCE, Kansas City, MO.

Boancă, P., Dumitraş, A., Luca, L., Bors-Oprișa, S. and Laczi, E. (2018) Analysing Bioretention Hydraulics and Runoff Retention through Numerical Modelling Using Recarga: A Case Study in a Romanian Urban Area. Polish Journal of Environmental Studies 27(5), 1965-1973. https://doi.org/10.15244/pjoes/79271

Bonneau, J., Fletcher, T.D., Costelloe, J.F., Poelsma, P.J., James, R.B. and Burns, M.J. (2018) Where Does Infiltrated Stormwater Go? Interactions with Vegetation and Subsurface Anthropogenic Features. Journal of Hydrology 567, 121-132. https://doi.org/10.1016/j.jhydrol.2018.10.006

Bosley, E.K. (2008) Hydrologic Evaluation of Low Impact Development Using a Continuous, Spatially-Distributed Model.

Braga, A., Horst, M. and Traver, R.G. (2007) Temperature Effects on the Infiltration Rate through an Infiltration Basin Bmp. Journal of Irrigation and Drainage Engineering 133(6), 593-601. https://doi.org/10.1061/(Asce)0733-9437(2007)133:6(593)

Brown, R.A. (2011) Evaluation of Bioretention Hydrology and Pollutant Removal in the Upper Coastal Plain of North Carolina with Development of a Bioretention Modeling Application in Drainmod. Doctoral dissertation, North Carolina State University, Raleigh, North Carolina.

Brown, R.A., Birgand, F. and Hunt, W.F. (2013a) Analysis of Consecutive Events for Nutrient and Sediment Treatment in Field-Monitored Bioretention Cells. Water Air and Soil Pollution 224(6). https://doi.org/ARTN158110.1007/s11270-013-1581-6

Brown, R.A. and Hunt, W.F. (2010) Impacts of Construction Activity on Bioretention Performance. Journal of Hydrologic Engineering 15(6), 386-394. https://doi.org/10.1061/(Asce)He.1943-5584.0000165

Brown, R.A. and Hunt, W.F. (2011a) Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells. Journal of Irrigation and Drainage Engineering 137(3), 132-143. https://doi.org/10.1061/(Asce)Ir.1943-4774.0000167

Brown, R.A. and Hunt, W.F. (2011b) Underdrain Configuration to Enhance Bioretention Exfiltration to Reduce Pollutant Loads. Journal of Environmental Engineering-Asce 137(11), 1082-1091. https://doi.org/10.1061/(Asce)Ee.1943-7870.0000437

Brown, R.A. and Hunt, W.F. (2012) Improving Bioretention/Biofiltration Performance with Restorative Maintenance. Water Science and Technology 65(2), 361-367. https://doi.org/10.2166/wst.2012.860

Brown, R.A., Skaggs, R.W. and Hunt, W.F. (2013b) Calibration and Validation of Drainmod to Model Bioretention Hydrology. Journal of Hydrology 486, 430-442. https://doi.org/10.1016/j.jhydrol.2013.02.017

Burns, M.J., Fletcher, T.D., Walsh, C.J., Ladson, A.R. and Hatt, B.E. (2012) Hydrologic Shortcomings of Conventional Urban Stormwater Management and Opportunities for Reform. Landscape and Urban Planning 105(3), 230-240. https://doi.org/10.1016/j.landurbplan.2011.12.012

Center for Neighborhood Technology (2007) Green Values Stormwater Calculator Methodology, Center for Neighborhood Technology, greenvalues.cnt.org.

Chapman, C. and Horner, R.R. (2010) Performance Assessment of a Street-Drainage Bioretention System. Water Environment Research 82(2), 109-119. https://doi.org/10.2175/106143009x426112

Chiew, F.H.S. and McMahon, T.A. (1997) Modelling Daily Runoff and Pollutant Load from Urban Catchments. Water 24, 16-17.

Christianson, R.D. (2003) Evaluation of the Soil and Water Assessment Tool for Urban Stormwater Management, Kansas State University, Manhattan, KS.

Dagenais, D., Brisson, J. and Fletcher, T.D. (2018) The Role of Plants in Bioretention Systems; Does the Science Underpin Current Guidance? Ecological Engineering 120, 532-545. https://doi.org/10.1016/j.ecoleng.2018.07.007

Davis, A.P. (2007) Field Performance of Bioretention: Water Quality. Environmental Engineering Science 24(8), 1048-1064. https://doi.org/10.1089/ees.2006.0190
Davis, A.P. (2008) Field Performance of Bioretention: Hydrology Impacts. Journal of Hydrologic Engineering 13(2), 90-95. https://doi.org/10.1061/(Asce)1084-0699(2008)13:2(90)
Davis, A.P., Hunt, W.F., Traver, R.G. and Clar, M. (2009) Bioretention Technology: Overview of Current Practice and Future Needs. Journal of Environmental Engineering 135(3), 109-117. https://doi.org/10.1061//ASCE/0733-9372/2009/135:3/109
Davis, A.P., Traver, R.G., Hunt, W.F., Lee, R., Brown, R.A. and Olszewski, J.M. (2012) Hydrologic Performance of Bioretention Storm-Water Control Measures. Journal of Hydrologic Engineering 17(5), 604-614. https://doi.org/10.1061/(Asce)He.1943-5584.0000467
DeGasperi, C.L. (2009) Development of a Stormwater Retrofit Plan for Water Resources Inventory Area 9: Sustain Model Pilot Study. Division, K.C.W.a.L.R. (ed), King County Department of Natural Resources and Parks, Seattle, WA.
DHI (2017) Mike Urban: Collection System-Modelling of Storm Water Drainage Networks and Sewer Collection Systems, User Guide.
Dietrich, A., Yarlagadda, R. and Gruden, C. (2017) Estimating the Potential Benefits of Green Stormwater Infrastructure on Developed Sites Using Hydrologic Model Simulation. Environmental Progress & Sustainable Energy 36(2), 557-564. https://doi.org/10.1002/ep.12428
Dietz, M.E. (2007) Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. Water, Air, and Soil Pollution 186(1-4), 351-363. https://doi.org/10.1007/s11270-007-9484-z
Dotto, C.B.S., Deletic, A., McCarthy, D.T. and Fletcher, T.D. (2011) Calibration and Sensitivity Analysis of Urban Drainage Models: Music Rainfall/Runoff Module and a Simple Stormwater Quality Model. Australasian Journal of Water Resources 15(1), 85-94. https://doi.org/10.1080/13241583.2011.11465392
Dussaillant, A., Cozzetto, K., Brander, K. and Potter, K. (2003) Green-Ampt Model of a Rain Garden and Comparison to Richard's Equation Model. Transactions on Ecology and the Environment 67, 891-900.
Elliott, A. and Trowsdale, S. (2007) A Review of Models for Low Impact Urban Stormwater Drainage. Environmental Modelling & Software 22(3), 394-405. https://doi.org/10.1016/j.envsoft.2005.12.005
Elliott, A.H., Trowsdale, S.A. and Wadhwa, S. (2009) Effect of Aggregation of on-Site Storm-Water Control
Devices in an Urban Catchment Model. Journal of Hydrologic Engineering, 14(9), 975-983. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000064
Emerson, C.H. and Traver, R.G. (2008) Multiyear and Seasonal Variation of Infiltration from Storm-Water Best Management Practices. Journal of Irrigation and Drainage Engineering 134(5), 598-605. https://doi.org/10.1061/(Asce)0733-9437(2008)134:5(598)

Ergas, S.J., Sengupta, S., Siege, R., Pandit, A., Yao, Y.F. and Yuan, X. (2010) Performance of Nitrogen-Removing Bioretention Systems for Control of Agricultural Runoff. Journal of Environmental Engineering-Asce 136(10), 1105-1112. https://doi.org/10.1061/(Asce)Ee.1943-7870.0000243

eWater (2013) Music by Ewater: User Manual.

Feddes, R.A., Kowalik, P.J. and Zaradny, H. (1978) Simulation of Field Water Use and Crop Yield, John Wiley & Sons, New York, NY.

Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P.S., Rivard, G., Uhl, M., Dagenais, D. and Viklander, M. (2014) Suds, Lid, Bmps, Wsud and More – the Evolution and Application of Terminology Surrounding Urban Drainage. Urban Water Journal 12(7), 525-542. https://doi.org/10.1080/1573062x.2014.916314

Gagrani, V., Diemer, J.A., Karl, J.J. and Allan, C.J. (2014) Assessing the Hydrologic and Water Quality Benefits of a Network of Stormwater Control Measures in a Se U.S. Piedmont Watershed. JAWRA Journal of the American Water Resources Association 50(1), 128-142. https://doi.org/10.1111/jawr.12121

Gao, J., Pan, J., Hu, N. and Xie, C. (2018) Hydrologic Performance of Bioretention in an Expressway Service Area. Water Sci Technol 77(7-8), 1829-1837. https://doi.org/10.2166/wst.2018.048

Garcia-Gutierrez, C., Pachepsky, Y. and Martin, M.A. (2018) Technical Note: Saturated Hydraulic Conductivity and Textural Heterogeneity of Soils. Hydrology and Earth System Sciences 22(7), 3923-3932. https://doi.org/10.5194/hess-22-3923-2018

Goh, H.W., Zakaria, N.A., Lau, T.L., Foo, K.Y., Chang, C.K. and Leow, C.S. (2017) Mesocosm Study of Enhanced Bioretention Media in Treating Nutrient Rich Stormwater for Mixed Development Area. Urban Water Journal 14(2), 134-142. https://doi.org/10.1080/1573062x.2015.1076861

Good, J.F., O'Sullivan, A.D., Wicke, D. and Cochrane, T.A. (2012) Contaminant Removal and Hydraulic Conductivity of Laboratory Rain Garden Systems for Stormwater Treatment. Water Science and Technology 65(12), 2154-2161. https://doi.org/10.2166/wst.2012.135

Gulbaz, S. and Kazezyilmaz-Alhan, C.M. (2017) An Evaluation of Hydrologic Modeling Performance of Epa Swmm for Bioretention. Water Sci Technol 76(11), 3035-3043. https://doi.org/10.2166/wst.2017.464

Gülbaz, S. and Kazezyılmaz-Alhan, C.M. (2017) Hydrological Model of Lid with Rainfall-Watershed-Bioretention System. Water Resources Management 31(6), 1931-1946. https://doi.org/10.1007/s11269-017-1622-9

Gwenzi, W., Hinz, C., Holmes, K., Phillips, I.R. and Mullins, I.J. (2011) Field-Scale Spatial Variability of Saturated Hydraulic Conductivity on a Recently Constructed Artificial Ecosystem. Geoderma 166(1), 43-56. https://doi.org/10.1016/j.geoderma.2011.06.010

Hamel, P. and Fletcher, T.D. (2014a) The Impact of Stormwater Source-Control Strategies on the (Low) Flow Regime of Urban Catchments. Water Sci Technol 69(4), 739-745. https://doi.org/10.2166/wst.2013.772

Hamel, P. and Fletcher, T.D. (2014b) Modelling the Impact of Stormwater Source Control Infiltration Techniques on Catchment Baseflow. Hydrological Processes 28(24), 5817-5831. https://doi.org/10.1002/hyp.10069

Hathaway, J.M., Brown, R.A., Fu, J.S. and Hunt, W.F. (2014) Bioretention Function under Climate Change Scenarios in North Carolina, USA. Journal of Hydrology 519, 503-511. https://doi.org/10.1016/j.jhydrol.2014.07.037

Hatt, B.E., Fletcher, T.D. and Deletic, A. (2009) Hydrologic and Pollutant Removal Performance of Stormwater Biofiltration Systems at the Field Scale. Journal of Hydrology 365(3-4), 310-321. https://doi.org/10.1016/j.jhydrol.2008.12.001

He, Z.X. and Davis, A.P. (2011) Process Modeling of Storm-Water Flow in a Bioretention Cell. Journal of Irrigation and Drainage Engineering 137(3), 121-131. https://doi.org/10.1061/(Asce)Ir.1943-4774.0000166

Heasom, W., Traver, R.G. and Welker, A.L. (2006) Hydrologic Modeling of a Bioinfiltration Best Management Practice. Journal of the American Water Resources Association 42(5), 1329-1347.

Hsieh, C.H. and Davis, A.P. (2005) Multiple-Event Study of Bioretention for Treatment of Urban Storm Water Runoff. Water Science and Technology 51(3-4), 177-181. <Go to ISI>://WOS:000228827100023

Hsieh, C.H., Davis, A.P. and Needelman, B.A. (2007a) Bioretention Column Studies of Phosphorus Removal from Urban Stormwater Runoff. Water Environment Research 79(2), 177-184. https://doi.org/10.2175/106143006x111745

Hsieh, C.H., Davis, A.P. and Needelman, B.A. (2007b) Nitrogen Removal from Urban Stormwater Runoff through Layered Bioretention Columns. Water Environment Research 79(12), 2404-2411. https://doi.org/10.2175/106143007x183844

Hunt, W.F., Jarrett, A.R., Smith, J.T. and Sharkey, L.J. (2006) Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. Journal of Irrigation and Drainage Engineering 132(6), 600-608. https://doi.org/10.1061/(Asce)0733-9437(2006)132:6(600)

Hunt, W.F., Kannan, N., Jeong, J. and Gassman, P.W. (2009) Stormwater Best Management Practices: Review of Current Practices and Potential Incorporation in Swat. International Agricultural Engineering Journal 18(1-2), 73-89.

Hunt, W.F., Smith, J.T., Jadlocki, S.J., Hathaway, J.M. and Eubanks, P.R. (2008) Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, Nc. Journal of Environmental Engineering-Asce 134(5), 403-408. https://doi.org/10.1061/(Asce)0733-9372(2008)134:5(403)

Imteaz, M.A., Ahsan, A., Rahman, A. and Mekanik, F. (2013) Modelling Stormwater Treatment Systems Using Music: Accuracy. Resources, Conservation and Recycling 71, 15-21. https://doi.org/10.1016/j.resconrec.2012.11.007

Jayasooriya, V.M. and Ng, A.W.M. (2014) Tools for Modeling of Stormwater Management and Economics of Green Infrastructure Practices: A Review. Water, Air, & Soil Pollution 225(8). https://doi.org/10.1007/s11270-014-2055-1

Jefferson, A.J., Bhaskar, A.S., Hopkins, K.G., Fanelli, R., Avellaneda, P.M. and McMillan, S.K. (2017) Stormwater Management Network Effectiveness and Implications for Urban Watershed Function: A Critical Review. Hydrological Processes 31(23), 4056-4080. https://doi.org/10.1002/hyp.11347

Jeong, J., Kannan, N., Arnold, J., Glick, R., Gosselink, L. and Srinivasan, R. (2010) Development and Integration of Sub-Hourly Rainfall–Runoff Modeling Capability within a Watershed Model. Water Resources Management 24(15), 4505-4527. https://doi.org/10.1007/s11269-010-9670-4

Jiang, C.B., Li, J.K., Li, H.E., Li, Y.J. and Chen, L. (2017) Field Performance of Bioretention Systems for Runoff Quantity Regulation and Pollutant Removal. Water Air and Soil Pollution 228(12). https://doi.org/ARTN 46810.1007/s11270-017-3636-6

Kabbes, K.C., McCracken, S. and Hood, J.W. (2008) Determining Cost Effective Pollution Reduction Bmp Scenarios for Low Impact Redevelopment and a Watershed Plan Using Winslamm, Seattle, WA.

Kaykhosravi, S., Khan, U. and Jadidi, A. (2018) A Comprehensive Review of Low Impact Development Models for Research, Conceptual, Preliminary and Detailed Design Applications. Water 10(11), 1541. https://doi.org/10.3390/w10111541

Khaniya, B., Wanniarachchi, S. and Rathnayake, U. (2017) Importance of Hydrologic Simulation for Lids and Bmps Design Using Hec-Hms: A Case Demonstration. International Journal of Hydrology 1(5), 138-146.

Kim, H., Mallari, K.J.B., Baek, J., Pak, G., Choi, H.I. and Yoon, J. (2019) Considering the Effect of Groundwater on Bioretention Using the Storm Water Management Model. J Environ Manage 231, 1270-1276. https://doi.org/10.1016/j.jenvman.2018.03.032

Kluge, B., Markert, A., Facklam, M., Sommer, H., Kaiser, M., Pallasch, M. and Wessolek, G. (2018) Metal Accumulation and Hydraulic Performance of Bioretention Systems after Long-Term Operation. Journal of Soils and Sediments 18(2), 431-441. https://doi.org/10.1007/s11368-016-1533-z

Komlos, J. and Traver, R.G. (2012) Long-Term Orthophosphate Removal in a Field-Scale Storm-Water Bioinfiltration Rain Garden. Journal of Environmental Engineering 138(10), 991-998. https://doi.org/10.1061/(Asce)Ee.1943-7870.0000566

L-Thia Low Impact Development Spreadsheet (2015), Purdue University.

Lai, F.-h., Shoemaker, L., Alvi, K., Riverson, J. and Zhen, J.X. (2010) Current Capabilities and Planned Enhancements of Sustain. Palmer, R.N. (ed), Providence, RI.

Lee, J.G., Selvakumar, A., Alvi, K., Riverson, J., Zhen, J.X., Shoemaker, L. and Lai, F.-h. (2012) A Watershed-Scale Design Optimization Model for Stormwater Best Management Practices. Environmental Modelling & Software 37, 6-18. https://doi.org/10.1016/j.envsoft.2012.04.011

Li, C., Fletcher, T.D., Duncan, H.P. and Burns, M.J. (2017) Can Stormwater Control Measures Restore Altered Urban Flow Regimes at the Catchment Scale? Journal of Hydrology 2017 v.549, pp. 631-653. https://doi.org/10.1016/j.jhydrol.2017.03.037

Li, H. and Davis, A.P. (2008a) Urban Particle Capture in Bioretention Media. I: Laboratory and Field Studies. Journal of Environmental Engineering-Asce 134(6), 409-418. https://doi.org/10.1061/(Asce)0733-9372(2008)134:6(409)

Li, H. and Davis, A.P. (2008b) Urban Particle Capture in Bioretention Media. Ii: Theory and Model Development. Journal of Environmental Engineering-Asce 134(6), 419-432. https://doi.org/10.1061/(Asce)0733-9372(2008)134:6(419)

Li, H. and Davis, A.P. (2009) Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention. Journal of Environmental Engineering 135(8), 567-576. https://doi.org/10.1061/(Asce)Ee.1943-7870.0000026

Li, H. and De Costa, G. (2016) Analysing Rain Garden Infiltration Efficiency Using Mouse Model.

Li, H., Sharkey, L.J., Hunt, W.F. and Davis, A.P. (2009) Mitigation of Impervious Surface Hydrology Using Bioretention in North Carolina and Maryland. Journal of Hydrologic Engineering 14(4), 407-415. https://doi.org/10.1061/(Asce)1084-0699(2009)14:4(407)

Li, J., Zhao, R., Li, Y. and Chen, L. (2018) Modeling the Effects of Parameter Optimization on Three Bioretention Tanks Using the Hydrus-1d Model. J Environ Manage 217, 38-46. https://doi.org/10.1016/j.jenvman.2018.03.078

Li, K., De Jong, R. and Boisvert, J. (2001) Comparison of Root-Water-Uptake Models.

Li, Z.Y. and Lam, K.M. (2015) Statistical Evaluation of Bioretention System for Hydrologic Performance. Water Science and Technology 71(11), 1742-1749. https://doi.org/10.2166/wst.2015.131

Line, D.E. and Hunt, W.F. (2009) Performance of a Bioretention Area and a Level Spreader-Grass Filter Strip at Two Highway Sites in North Carolina. Journal of Irrigation and Drainage Engineering 135(2), 217-224. https://doi.org/10.1061/(Asce)0733-9437(2009)135:2(217)

Lisenbee, W., Hathaway, J., Negm, L., Youssef, M. and Winston, R. (2020) Enhanced Bioretention Cell Modeling with Drainmod-Urban: Moving from Water Balances to Hydrograph Production. Journal of Hydrology 582, 124491. https://doi.org/https://doi.org/10.1016/j.jhydrol.2019.124491

Liu, J., Sample, D., Bell, C. and Guan, Y. (2014a) Review and Research Needs of Bioretention Used for the Treatment of Urban Stormwater. Water 6(4), 1069-1099. https://doi.org/10.3390/w6041069

Liu, J., Sample, D.J., Owen, J.S., Li, J.L. and Evanylo, G. (2014b) Assessment of Selected Bioretention Blends for Nutrient Retention Using Mesocosm Experiments. Journal of Environmental Quality 43(5), 1754-1763. https://doi.org/10.2134/jeq2014.01.0017

Liu, R.F. and Fassman-Beck, E. (2017) Hydrologic Experiments and Modeling of Two Laboratory Bioretention Systems under Different Boundary Conditions. Frontiers of Environmental Science & Engineering 11(4). https://doi.org/ARTN 1010.1007/s11783-017-0951-5

Lopez, E.V., Lynn, T.J., Peterson, M., Ergas, S.J., Trotz, M.A. and Mihelcic, J.R. (2016) Enhanced Nutrient Management of Stormwater through a Field Demonstration of Nitrogen Removal in a Modified Bioretention System. World Environmental and Water Resources Congress 2016: Environmental, Sustainability, Groundwater, Hydraulic Fracturing, and Water Distribution Systems Analysis, 60-69. <Go to ISI>://WOS:000389439700007

Lucas, W. (2008) Continuous Simulation of Integrated Bioretention-Infiltration Systems for Urban Retrofits, Seattle, WA.

Lucas, W. (2010) Design of Integrated Bioinfiltration-Detention Urban Retrofits with Design Storm and Continuous Simulation Methods. J. Hydrol. Eng. 15(6), 486-498. https://doi.org/10.1061//ASCE/HE.1943-5584.0000137

Lucas, W.C. and Greenway, M. (2008) Nutrient Retention in Vegetated and Nonvegetated Bioretention Mesocosms. Journal of Irrigation and Drainage Engineering 134(5), 613-623. https://doi.org/10.1061/(Asce)0733-9437(2008)134:5(613)

Lucas, W.C. and Greenway, M. (2011a) Hydraulic Response and Nitrogen Retention in Bioretention Mesocosms with Regulated Outlets: Part I-Hydraulic Response. Water Environment Research 83(8), 692-702. https://doi.org/10.2175/106143010x12780288628697

Lucas, W.C. and Greenway, M. (2011b) Hydraulic Response and Nitrogen Retention in Bioretention Mesocosms with Regulated Outlets: Part Ii-Nitrogen Retention. Water Environment Research 83(8), 703-713. https://doi.org/10.2175/106143011x12989211840936

Lucas, W.C. and Greenway, M. (2011c) Phosphorus Retention by Bioretention Mesocosms Using Media Formulated for Phosphorus Sorption: Response to Accelerated Loads. Journal of Irrigation and Drainage Engineering 137(3), 144-153. https://doi.org/10.1061/(Asce)Ir.1943-4774.0000243

Lucke, T., Dierkes, C. and Boogaard, F. (2017) Investigation into the Long-Term Stormwater Pollution Removal Efficiency of Bioretention Systems. Water Science and Technology 76(8), 2133-2139. https://doi.org/10.2166/wst.2017.382

Lucke, T. and Nichols, P.W.B. (2015) The Pollution Removal and Stormwater Reduction Performance of Street-Side Bioretention Basins after Ten Years in Operation. Science of the Total Environment 536, 784-792. https://doi.org/10.1016/j.scitotenv.2015.07.142

Lynn, T.J., Nachabe, M.H. and Ergas, S.J. (2018) Swmm5 Unsaturated Drainage Models for Stormwater Biofiltration with an Internal Water Storage Zone. Journal of Sustainable Water in the Built Environment 4(1), 04017018. https://doi.org/10.1061/jswbay.0000844

Machusick, M., Welker, A. and Traver, R. (2011) Groundwater Mounding at a Storm-Water Infiltration Bmp. Journal of Irrigation and Drainage Engineering 137(3), 154-160. https://doi.org/10.1061/(Asce)Ir.1943-4774.0000184

Massoudieh, A. and Aflak, S. (2017) User's Manual for Green Infrastructure Flexible Model (Gifmod).

Massoudieh, A., Maghrebi, M., Kamrani, B., Nietch, C., Tryby, M., Aflaki, S. and Panguluri, S. (2017) A Flexible Modeling Framework for Hydraulic and Water Quality Performance Assessment of Stormwater Green Infrastructure. Environmental Modelling & Software 92, 57-73. https://doi.org/10.1016/j.envsoft.2017.02.013

McCutcheon, M. and Wride, D. (2013) Shades of Green: Using Swmm Lid Controls to Simulate Green Infrastructure. Journal of Water Management Modeling. https://doi.org/10.14796/jwmm.r246-15

Meng, Y., Wang, H., Chen, J. and Zhang, S. (2014) Modelling Hydrology of a Single Bioretention System with Hydrus-1d. ScientificWorldJournal 2014, 521047. https://doi.org/10.1155/2014/521047

Montgomery, R.J., Gaffield, S.J., Sigmarrson, S.G., Severson, L.M. and Lefers, J.D. (2010) The Challenges of Mitigating Hydrologic Impacts of Development: Lessons Learned in Dane County, Wisconsin, American Society of Civil Engineers, Madison, WI.

Muthanna, T.M., Viklander, M. and Thorolfsson, S.T. (2007) An Evaluation of Applying Existing Bioretention Sizing Methods to Cold Climates with Snow Storage Conditions. Water Sci Technol 56(10), 73-81. https://doi.org/10.2166/wst.2007.745

Muthanna, T.M., Viklander, M. and Thorolfsson, S.T. (2008) Seasonal Climatic Effects on the Hydrology of a Rain Garden. Hydrological Processes 22(11), 1640-1649. https://doi.org/10.1002/hyp.6732

National Research Council (2009) Urban Stormwater Management in the United States, The National Academies Press, Washington, DC.

North Carolina Department of Enviromental Quality (2009) Ncdenr Stormwater Bmp Manual

Ohio Department of Natural Resources (2006) Rainwater and Land Development: Ohio's Standards for Stormwater Management Land Development and Urban Stream Protection. Ohio Department of Natural Resources, D.o.S.a.W.C. (ed), Columbus, OH.

Olszewski, J.M. and Davis, A.P. (2013) Comparing the Hydrologic Performance of a Bioretention Cell with Predevelopment Values. Journal of Irrigation and Drainage Engineering 139(2), 124-130. https://doi.org/10.1061/(Asce)Ir.1943-4774.0000504

Palmer, E.T., Poor, C.J., Hinman, C. and Stark, J.D. (2013) Nitrate and Phosphate Removal through Enhanced Bioretention Media: Mesocosm Study. Water Environment Research 85(9), 823-832. https://doi.org/10.2175/106143013x13736496908997

Papanicolaou, A.N., Elhakeem, M., Wilson, C.G., Burras, C.L., West, L.T., Lin, H., Clark, B. and Oneal, B.E. (2015) Spatial Variability of Saturated Hydraulic Conductivity at the Hillslope Scale: Understanding the Role of Land Management and Erosional Effect. Geoderma 243, 58-68. https://doi.org/10.1016/j.geoderma.2014.12.010

Paus, K.H., Morgan, J., Gulliver, J.S., Leiknes, T. and Hozalski, R.M. (2014) Assessment of the Hydraulic and Toxic Metal Removal Capacities of Bioretention Cells after 2 to 8 Years of Service. Water Air and Soil Pollution 225(1). https://doi.org/ARTN 180310.1007/s11270-013-1803-y

Payne, E.G.I., Fletcher, T.D., Russell, D.G., Grace, M.R., Cavagnaro, T.R., Evrard, V., Deletic, A., Hatt, B.E. and Cook, P.L.M. (2014) Temporary Storage or Permanent Removal? The Division of Nitrogen between Biotic Assimilation and Denitrification in Stormwater Biofiltration Systems. PLoS One 9(3). https://doi.org/ARTN e9089010.1371/journal.pone.0090890

Payne, E.G.I., Pham, T., Deletic, A., Hatt, B.E., Cook, P.L.M. and Fletcher, T.D. (2018) Which Species? A Decision-Support Tool to Guide Plant Selection in Stormwater Biofilters. Advances in Water Resources 113, 86-99. https://doi.org/10.1016/j.advwatres.2017.12.022

Pitt, R.E. (1999) Small Storm Hydrology and Why It Is Important for the Design of Stormwater Control Practices. Journal of Water Management Modeling. https://doi.org/10.14796/jwmm.r204-04

Pitt, R.E. and Voorhees, J. (2004) Winslamm and Low Impact Development, College Park, MD.

Rawls, W.J., Brakensiek, D.L. and Miller, N. (1983) Green-Ampt Infiltration Parameters from Soils Data. Journal of Hydraulic Engineering-Asce 109(1), 62-70. https://doi.org/Doi 10.1061/(Asce)0733-9429(1983)109:1(62)

Rawls, W.J., Gimenez, D. and Grossman, R. (1998) Use of Soil Texture, Bulk Density, and Slope of the Water Retention Curve to Predict Saturated Hydraulic Conductivity. Transactions of the Asae 41(4), 983-988. <Go to ISI>://WOS:000075662800010

Ray, C., Bezak, B., Petrey, K. and Shea, E. (2015) Measurement and Optimization of Permeability in Bioretention Soil Media. Lid: It Works in All Climates and Soils, 176-185. <Go to ISI>://WOS:000381031400018

Rosa, D.J., Clausen, J.C. and Dietz, M.E. (2015) Calibration and Verification of Swmm for Low Impact Development. Journal of the American Water Resources Association 51(3), 746-757. https://doi.org/10.1111/jawr.12272

Rossman, L.A. (2010) Modeling Low Impact Development Alternatives with Swmm. Journal of Water Management Modeling. https://doi.org/10.14796/jwmm.r236-11

Rossman, L.A. and Bernagros, J.T. (2018) National Stormwater Calculator User's Guide – Version 1.2.0.1. Division, W.S. and Laboratory, N.R.M.R. (eds), Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH.

Rossman, L.A. and Huber, W.C. (2016a) Storm Water Management Model Reference Manual Volume Iii – Water Quality. Division, O.o.R.a.D.W.S.a.W.R. (ed), National Risk Management Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cinncinati, OH.

Rossman, L.A. and Huber, W.C. (2016b) Storm Water Management Model Reference Manual: Volume I – Hydrology (Revised). Division, O.o.R.a.D.W.S.a.W.R. (ed), National Risk Management Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH.

Roy-Poirier, A., Champagne, P. and Filion, Y. (2010) Review of Bioretention System Research and Design: Past, Present, and Future. Journal of Environmental Engineering 136(9), 878-889. https://doi.org/10.1061/(Asce)Ee.1943-7870.0000227

Roy-Poirier, A., Filion, Y. and Champagne, P. (2015) An Event-Based Hydrologic Simulation Model for Bioretention Systems. Water Sci Technol 72(9), 1524-1533. https://doi.org/10.2166/wst.2015.368

Šejna, M., Šimůnek, J. and van Genuchten, M.T. (2014) Hydrus User Manual: Version 2.04, PC-Progress, Prague, Czech Republic.

Seo, M., Jaber, F., Srinivasan, R. and Jeong, J. (2017) Evaluating the Impact of Low Impact Development (Lid) Practices on Water Quantity and Quality under Different Development Designs Using Swat. Water 9(3), 193. https://doi.org/10.3390/w9030193

Shoemaker, L., Riverson, J.J., Alvi, K., Zhen, J.X. and Murphy, R. (2011) Report on Enhanced Framework (Sustain) and Field Applications for Placement of Bmps in Urban Watersheds. Office of Research and Development, N.R.M.R.L.-W.S.a.W.R.D. (ed), National Risk Management Research Laboratory, Office of Research and Development, Cincinnati, OH.

Shoemaker, L., Riverson, J.J., Alvi, K., Zhen, J.X., Murphy, R. and Wood, B. (2013) Stormwater Management for Tmdls in an Arid Climate: A Case Study Application of Sustain in Albuquerque, New Mexico. Development, O.o.R.a. (ed), National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH.

Shoemaker, L., Riverson, J.J., Alvi, K., Zhen, J.X., Paul, S. and Rafi, T. (2009) Sustain - a Framework for Placement of Best Management Practices in Urban Watersheds to Protect Water Quality Report. Development, O.o.R.a. and Division, N.R.M.R.L.-W.S.a.W.R. (eds), National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH.

Stander, E.K. and Borst, M. (2010) Hydraulic Test of a Bioretention Media Carbon Amendment. Journal of Hydrologic Engineering 15(6), 531-536. https://doi.org/10.1061/(Asce)He.1943-5584.0000133

Stewart, R.D., Lee, J.G., Shuster, W.D. and Darner, R.A. (2017) Modelling Hydrological Response to a Fully-Monitored Urban Bioretention Cell. Hydrological Processes 31(26), 4626-4638. https://doi.org/10.1002/hyp.11386

Sun, Y.-w., Li, Q.-y., Liu, L., Xu, C.-d. and Liu, Z.-p. (2014) Hydrological Simulation Approaches for Bmps and Lid Practices in Highly Urbanized Area and Development of Hydrological Performance Indicator System. Water Science and Engineering 7(2), 143-154. https://doi.org/10.3882/j.issn.1674-2370.2014.02.003

Sun, Y.-w., Wei, X.-m.C. and Pomeroy, C.A. (2011) Global Analysis of Sensitivity of Bioretention Cell Design Elements to Hydrologic Performance. Water Science and Engineering, 4(3), 246-257. https://doi.org/10.3882/j.issn.1674-2370.2011.03.002

Tiveron, T., Gholamreza-Kashi, S. and Joksimovic, D. (2018) A Usepa Swmm Integrated Tool for Determining the Suspended Solids Reduction Performance of Bioretention Cells. Journal of Water Management Modeling 26. https://doi.org/Artn C44310.14796/Jwmm.C443

Turney, I.D. and Neilson, B. (2010) Ultra Urban Green Street Design Criteria. Struck, S. and Lichten, K. (eds), pp. 642-660, American Society of Civil Engineers, San Francisco, CA.

U.S. Army Corps of Engineers (2018) Hydrologic Modeling System Hec-Hms User's Manual. Hydrologic Engineering Center and Institute for Water Resources (eds), Davis, CA.

van Genuchten, M.T. (1985) Convective-Dispersive Transport of Solutes Involved in Sequential First-Order Decay Reactions. Computers & Geosciences 11(2), 129-147.

Wadzuk, B.M., Hickman, J.M. and Traver, R.G. (2015) Understanding the Role of Evapotranspiration in Bioretention: Mesocosm Study. Journal of Sustainable Water in the Built Environment 1(2). https://doi.org/Artn 0401400210.1061/Jswbay.0000794

Wan, Z.X., Li, T. and Liu, Y.T. (2018) Effective Nitrogen Removal During Different Periods of a Field-Scale Bioretention System. Environmental Science and Pollution Research 25(18), 17855-17861. https://doi.org/10.1007/s11356-018-1954-x

Wang, J., Chua, L.H.C. and Shanahan, P. (2017) Evaluation of Pollutant Removal Efficiency of a Bioretention Basin and Implications for Stormwater Management in Tropical Cities. Environmental Science-Water Research & Technology 3(1), 78-91. https://doi.org/10.1039/c6ew00285d

Wang, M., Zhang, D.Q., Li, Y., Hou, Q.H., Yu, Y.Y., Qi, J.D., Fu, W.C., Dong, J.W. and Cheng, Y.N. (2018) Effect of a Submerged Zone and Carbon Source on Nutrient and Metal Removal for Stormwater by Bioretention Cells. Water 10(11). https://doi.org/ARTN 162910.3390/w10111629

Warrick, A.W. and Nielsen, D.R. (1980) Applications of Soil Physics. Hill, D. (ed), pp. 319–344, Academic Press, Inc., New York.

Water Balance Model Powered by Qualhymo: Technical Manual (2019), The Partnership for Water Sustainability.

Wilson, C.E., Hunt, W.F., Winston, R.J. and Smith, P. (2015) Comparison of Runoff Quality and Quantity from a Commercial Low-Impact and Conventional Development in Raleigh, North Carolina. Journal of Environmental Engineering 141(2), 05014005. https://doi.org/doi:10.1061/(ASCE)EE.1943-7870.0000842

Winston, R.J. (2015) Resilience of Green Infrastructure under Extreme Conditions. Doctoral dissertation. North Carolina State University, Raleigh, North Carolina.

Winston, R.J., Dorsey, J.D. and Hunt, W.F. (2016) Quantifying Volume Reduction and Peak Flow Mitigation for Three Bioretention Cells in Clay Soils in Northeast Ohio. Sci Total Environ 553, 83-95. https://doi.org/10.1016/j.scitotenv.2016.02.081

Wong, T.H.F., Fletcher, T.D., Duncan, H.P., Coleman, J.R. and Jenkins, G.A. (2002) A Model for Urban Stormwater Improvement Conceptualisation, pp. 48-53, American Society of Civil Engineers, Portland, Oregon.

Wong, T.H.F., Fletcher, T.D., Duncan, H.P. and Jenkins, G.A. (2006) Modelling Urban Stormwater Treatment—a Unified Approach. Ecological Engineering 27(1), 58-70. https://doi.org/10.1016/j.ecoleng.2005.10.014

Wright, O.M., Istanbulluoglu, E., Horner, R.R., DeGasperi, C.L. and Simmonds, J. (2018) Is There a Limit to Bioretention Effectiveness? Evaluation of Stormwater Bioretention Treatment Using a Lumped Urban Ecohydrologic Model and Ecologically Based Design Criteria. Hydrological Processes 32(15), 2318-2334. https://doi.org/10.1002/hyp.13142

Xie, J., Chenab, H., Liao, Z., Gua, X., Zhu, D. and Zhang, J. (2017) An Integrated Assessment of Urban Flooding Mitigation Strategies for Robust Decision Making. Environmental Modelling & Software 95, 143-155. https://doi.org/https://doi.org/10.1016/j.envsoft.2017.06.027

Yang, X.H., Mei, Y., He, J., Jiang, R., Li, Y.Q. and Li, J.Q. (2014) Comprehensive Assessment for Removing Multiple Pollutants by Plants in Bioretention Systems. Chinese Science Bulletin 59(13), 1446-1453. https://doi.org/10.1007/s11434-014-0200-2

Yang, Y. and Chui, T.F.M. (2018) Optimizing Surface and Contributing Areas of Bioretention Cells for Stormwater Runoff Quality and Quantity Management. J Environ Manage 206, 1090-1103. https://doi.org/10.1016/j.jenvman.2017.11.064

Zhang, G., Hamlett, J.M. and Saravanapavan, T. (2010) Representation of Low Impact Development Scenarios in Swmm. Journal of Water Management Modeling. https://doi.org/10.14796/jwmm.r236-12

Zhang, K. and Chui, T.F.M. (2017) Evaluating Hydrologic Performance of Bioretention Cells in Shallow Groundwater. Hydrological Processes 31(23), 4122-4135. https://doi.org/10.1002/hyp.11308

Zhang, K. and Chui, T.F.M. (2018) Interactions between Shallow Groundwater and Low-Impact Development Underdrain Flow at Different Temporal Scales. Hydrological Processes 32(23), 3495-3512. https://doi.org/10.1002/hyp.13272

Zhang, K., Chui, T.F.M. and Yang, Y. (2018a) Simulating the Hydrological Performance of Low Impact Development in Shallow Groundwater Via a Modified Swmm. Journal of Hydrology 566, 313-331. https://doi.org/10.1016/j.jhydrol.2018.09.006

Zhang, L., Lu, Q., Ding, Y., Peng, P. and Yao, Y. (2018b) Design and Performance Simulation of Road Bioretention Media for Sponge Cities. J. Perform. Constr. Facil. 32(5). https://doi.org/10.1061/(ASCE)CF.1943-5509.0001209.©2018

Zhang, S. and Guo, Y. (2013) Stormwater Capture Efficiency of Bioretention Systems. Water Resources Management 28(1), 149-168. https://doi.org/10.1007/s11269-013-0477-y

CHAPTER II

ENHANCED BIORETENTION CELL MODELING WITH DRAINMOD-URBAN: MOVING FROM WATER BALANCES TO HYDROGRAPH PRODUCTION

A version of this chapter was originally published by Whitney Lisenbee, Jon Hathaway, Lamyaa Negm, Mohamed Youssef, and Ryan Winston:

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2.1 Abstract

Bioretention systems have become a leading stormwater control measure for mitigating urban hydrology. Although these systems have performed well in many site-scale field studies, less investigation has been directed toward effectively modeling these systems. This is critical, as modeling of bioretention systems provides an avenue for evaluating their effectiveness prior to devoting time and resources into installation. Many hydrologic models capable of simulating bioretention consist of lumped parameters and simplifications that do not fully account for fundamental hydrologic processes such as soil-water interactions. DRAINMOD has shown promise for obtaining detailed daily water balances within bioretention systems under continuous simulations. One significant advantage of DRAINMOD is that it uses the soil-water characteristic curve to account for fluctuations in soil moisture instead of assuming saturation; however, the model historically only produces daily outputs. For this study, DRAINMOD was modified to develop DRAINMOD-Urban, which allows high temporal resolution inputs and outputs, more closely matching the residence time of runoff in urban systems. DRAINMOD-Urban simulations of a bioretention

cell in Ohio, USA, revealed that DRAINMOD-Urban could effectively produce hydrographs with a cumulative Nash-Sutcliffe Efficiency (NSE) of 0.60 for the 12 events that produced drainage over a 7-month monitoring period. Overflow was also modeled by DRAINMOD-Urban, but additional overflow data is necessary to derive conclusions about model effectiveness in predicting this hydrologic component. Input parameters previously calibrated for the DRAINMOD model did not translate well to DRAINMOD-Urban with the top-down approach applied in this study (NSE=0.31 for drainage and NSE=-1.83 for overflow), but the bottom-up approach showed that parameters calibrated with DRAINMOD-Urban (NSE=0.60 for drainage and NSE=-0.1 for overflow) could be used in DRAINMOD to obtain reasonable drainage volumes (25.6% error compared to measured values). This study suggests DRAINMOD-Urban is an effective tool for modeling bioretention hydrographs and demonstrates the importance of temporal scale in bioretention modeling by illustrating multiple model calibration approaches. Despite the promising results of this study, additional studies are recommended where validation of the model is performed at more sites, in particular for events with overflow. Further, sensitivity analysis of input parameters and comparison of DRAINMOD-Urban to other commonly used bioretention models would inform future modeling efforts.

2.2 Introduction

Changes in stormwater management approaches over the past few decades have led to more sustainable stormwater controls that aspire to restore urban streams and watersheds by returning them to a more natural hydrologic regime (Fletcher et al., 2014). Bioretention cells are one of the most popular stormwater controls, aiming to reduce urban runoff volumes and peak flows which alter the hydrology of local waterways (Dietrich et al., 2017). However, bioretention research has primarily focused on field monitoring studies and laboratory assessments (Liu et al., 2014a; Davis et al., 2009). Computational models have been slow to develop for bioretention systems despite the importance of being able to evaluate these systems prior to investment of time, money, and resources. Further, modeling of bioretention allows designers to optimize bioretention cell design and performance, provide guidance for design standards, and scale local impacts to the larger watershed. Developing widely-available, effective models for bioretention systems could lead to increased adoption of these systems (Elliott and Trowsdale, 2007).

Several deficiencies are present in currently utilized bioretention models. Many existing models applied to bioretention use simplifications that do not adequately represent fundamental hydrologic processes. Another limitation of current bioretention models is the inability to effectively simulate either underdrains or internal water storage (IWS) zones despite widespread use of these features in field applications (Brown, 2011). Additionally, early bioretention models lacked long-term, continuous simulations which ignored the effect of antecedent moisture conditions in the soil, an important consideration that affects the infiltration and storage capabilities of the system (Davis et al., 2009; Heasom et al., 2006). Further, many models use infiltration processes that assume uniform saturation of the media, such as the Green-Ampt equation or a constant user-input infiltration rate (Kaykhosravi et al., 2018; Lee et al., 2013). However, field measurements confirm bioretention systems are variably saturated and unsaturated during and following rain events (Brown et al., 2013b). As an example of the importance of these assumptions, in the mathematical bioretention model developed by Guo and Luu (2015), the hydraulic conductivity and initial soil moisture were the primary calibration parameters emphasizing the significance of soil-moisture accounting in bioretention modeling. These shortcomings need to be addressed in order to adequately model the hydrologic processes of bioretention systems.

DRAINMOD is historically an agricultural drainage model that has shown promise when applied to bioretention systems. DRAINMOD overcomes many limitations of other bioretention models by allowing continuous simulation that provides detailed water balances and the ability to model IWS zones through its weir settings. One major advantage of this model is that it uses the soil-water characteristic curve (SWCC) to account for fluctuations in soil moisture such as the drainage volume and upward flux with respect to water table depth. This is important for the calculation of infiltration under unsaturated or partially saturated conditions which dominate bioretention operation (Winston et al., 2016; Barbu and Ballestero, 2015).

Initial studies that evaluated DRAINMOD for bioretention applications showed favorable results (Winston, 2015; Hathaway et al., 2014; Brown et al., 2013b). Brown et al. (2013) and Brown (2011) were the first studies to investigate DRAINMOD to model the bioretention hydrology. Calibration and validation of the model showed good agreement with measured data with Nash-Sutcliffe efficiencies (NSE) ranging from 0.6-0.9 for daily drainage, overflow, and exfiltration of four bioretention cells. These initial investigations were followed by Winston (2015), who modeled three bioretention cells in Ohio, USA, in DRAINMOD with daily outputs. This study obtained excellent agreement between model predictions and measured values, with NSE ranging from 0.73-0.98 for the validation period. These studies proved that DRAINMOD, with its ability to model IWS zones and its improved soil-moisture accounting, can accurately model long-term water balances through a bioretention cell.

However, the biggest disadvantage of DRAINMOD for urban environments is that it aggregates outputs at a daily time step, only producing daily volumes of flow within each water balance component. It cannot produce hydrographs at a temporal scale that is consistent with the flashy nature of urban catchments and therefore loses some of the temporal dynamics of the system during storm events (Baffaut et al., 2015). Such outputs are critical to exploring event-based performance of bioretention cells, estimating flood mitigation, and allowing the model to be incorporated into larger watershed-scale models.

For this study, DRAINMOD (v. 6.1) has been modified to create DRAINMOD-Urban, an enhanced version that allows high temporal resolution inputs and outputs, more closely matching the hydrology of urban systems. Using a bioretention cell previously monitored by Winston et al. (2016), the objectives of this research were to: 1) assess if DRAINMOD-Urban can produce accurate output hydrographs compared to measured data and 2) compare DRAINMOD and DRAINMOD-Urban model performance for simulating bioretention hydrology using top-down and bottom-up approaches to parameterization.

2.3 Materials and Methods

2.3.1 Site Description

Data collected at a bioretention cell at Ursuline College (UC), located near Cleveland, Ohio, USA, was utilized to test the new DRAINMOD-Urban model. Initial characterization of the site was performed by Winston et al. (2016). The cell was originally modeled in DRAINMOD by Winston (2015) as summarized below.

Cleveland, OH, USA has a humid, continental climate [Köppen Dfa (Kottek et al., 2006)] with cold winters. The UC cell was designed to treat stormwater runoff from a 77% impervious drainage area (3600 m^2) made up primarily of parking lot. According to the Ohio Rainwater and Land Development Manual (Ohio Department of Natural Resources, 2006), design guidelines require a bioretention cell to store the water quality volume in Ohio (19 mm) within the ponding zone (i.e. no subsurface or dynamic storage is considered in the design). The UC cell was constructed in April-May of 2014 with a surface area of 182 m^2 (6.5% of the impervious contributing area). The ponding zone was 30 cm deep, exceeding the minimum required water quality capture volume described above. The bowl storage is atop a small mulch layer (8 cm) followed by a typical bioretention media (87% sand, 4% silt, 9% clay) with a depth of 60 cm (Figure 2.1). Underneath the bioretention media was a choking sand-stone layer (15 cm) just above a 30 cm layer of gravel. The final gravel layer rested on top of a 10 cm perforated PVC underdrain pipe with an upturned elbow to create a 60 cm IWS zone. The design parameters are summarized in Table 2.1. The UC cell was planted with 1450 plugs following construction which were still establishing during the monitoring period and are not expected to affect the hydrology of the system.

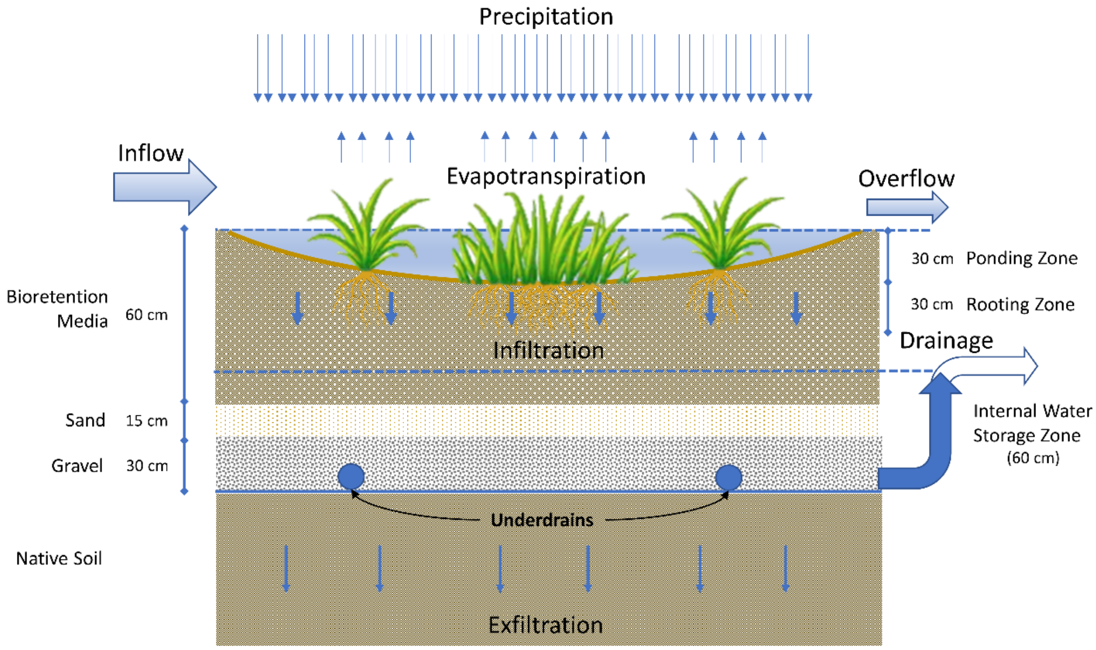


Figure 2.1 Schematic of the Ursuline College (UC) bioretention cell with underdrains and internal water storage (IWS). Flow of water balance components is designated by arrows.

Table 2.1 Design characteristics of the Ursuline College (UC) bioretention cell (Winston et al., 2016)

Characteristics	UC
Location	Pepper Pike, OH
Catchment Area (m^2)	3600
Catchment Imperviousness (%)	77
Bioretention Surface Area (m^2)	182
Loading Ratio (LR)[1]	19.8
As-built Design Event (mm)	29.5
Ponding Depth (m)	0.3
Mulch Layer Thickness (m)	0.08
Fill Media Depth (m)	0.6
Choking Stone + Sand Layer Thickness (m)	0.15
Gravel Layer Thickness (m)	0.3
Drainage Configuration	Underdrain; IWS
Underdrain Pipe Diameter (cm)	10
IWS Zone Depth (m)	0.6
Fill Media Characteristics	87% sand, 4% silt, 9% clay
Fill Media Organic Matter (by weight)	4.3%
Fill Media Textural Classification	Loamy Sand
Fill Media Ksat (mm/hr)	168
Underlying Soil Type	Mahoning silt loam and fill
Drawdown Rate (mm/hr)	4.3
Vegetation	Forbs and perennial grasses

[1] defined as the ratio of catchment area to bioretention surface area

2.3.2 Data Collection

All monitoring equipment collected data over a 7-month period at 1-minute or 2-minute intervals. A U30 weather station (Onset Computer Corporation, Bourne, MA) was installed at the UC site to collect wind speed, wind direction, air temperature, relative humidity, and solar radiation. Precipitation was measured on-site at a 1-minute interval using a 0.254-mm resolution tipping-bucket rain gauge (Davis Instruments, Hayward, California). Soil analysis was performed for the bioretention media to find the K_{sat} and SWCC following procedures outlined by Klute (1986).

The inflow entering the UC cell was diffuse sheet flow. Therefore, it was not feasible to measure inflow using a flume or weir. Alternatively, the US EPA's Storm Water Management Model (SWMM) v5.1.007 (Rossman and Huber, 2016b) was used to estimate the inflow hydrographs on a 1-minute time step. The default surface runoff method in SWMM is a nonlinear reservoir model that incorporates Manning’s equation for overland flow and accounts for depression storage. The infiltration was determined through the Green-Ampt model with estimations of soil properties based on soil texture.

The outlet of the UC cell was monitored using a 60-degree, sharp-crested, v-notch weir, and a Hobo U20 pressure transducer that collected data every two minutes (Onset Computer Corporation, Bourne, MA). Both drainage and overflow left via the outlet, necessitating additional techniques to separate these two hydrologic pathways (as described below). The internal water level was measured with a shallow monitoring well and a U20 pressure transducer. This measurement was used to find the drawdown rate (mm/hr) in the UC cell by observing the change in water level during inter-event periods. The average drawdown rate was calculated to represent the average combined exfiltration and ET releasing water from the cell between storm events.

Modeling in SWMM was performed to separate drainage from overflow at UC as described by Winston et al. (2016). Briefly, the bioretention cell was represented as a storage unit in SWMM with a controlled outlet. The discharge from this model was compared to the measured internal water level to create a rating curve. The rating curve was then used to predict a drainage hydrograph for each storm event. The overflow was determined from the difference of the modeled drainage hydrograph and the measured combined outflow hydrograph.

2.3.3 DRAINMOD Processes

DRAINMOD is a process-based, field-scale, whole system model that simulates the hydrology, water quality, crop growth, and yield for crop production systems on artificially drained shallow water table soils (Negm et al., 2014; Skaggs et al., 2012; Youssef et al., 2005). The hydrologic component of the model runs on hourly or daily time steps. The outputs of the model are summarized on a daily, monthly, yearly and ranked bases. A detailed description of modeling the various hydrologic processes in DRAINMOD can be found in Skaggs et al. (2012). In this paper, we briefly describe the hydrologic component of DRAINMOD with focus on processes that are relevant to model application to bioretention cells (Saraswat et al., 2015).

DRAINMOD simulates field hydrology using a simple water balance approach (Figure 2.2). The model conducts a water balance at the soil surface as follows:

$$P = F + \Delta S + RO \tag{1}$$

where P is the precipitation (cm), F is infiltration (cm), ΔS is the change in surface storage (cm), and RO is the runoff (cm). Once the precipitation exceeds infiltration, water ponds on the surface and depressional storage is filled. In bioretention cells, this surface storage refers to the ponding zone which is often designed to hold the water quality volume. When the surface storage is full, ΔS is zero, and the resulting surface runoff can be calculated as $RO = P - F$. In a bioretention cell, this process results in overflow.

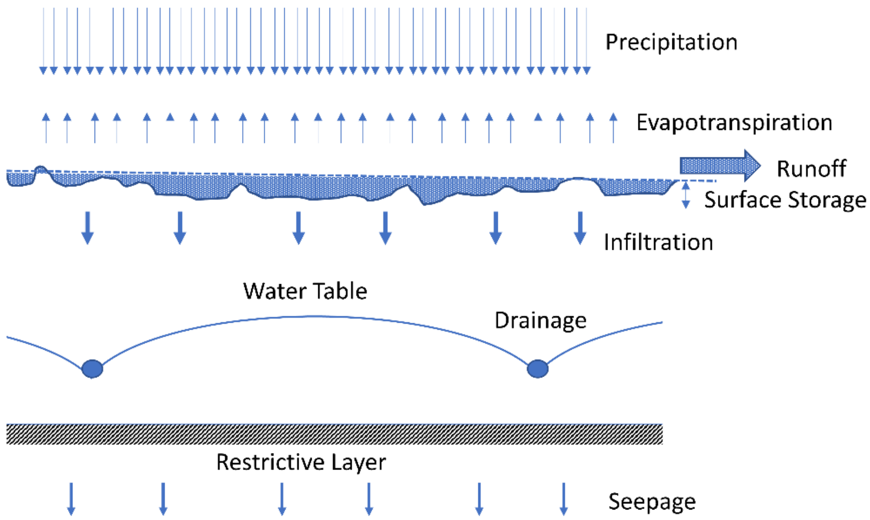


Figure 2.2 Schematic of the surface and subsurface hydrology as depicted in DRAINMOD.

The model also conducts another water balance for a soil section midway between drains and extending from the soil surface down to an impermeable layer. This water balance describes the available pore space in relation to the infiltrated water entering that soil layer, and the drainage, seepage, and ET leaving that layer. Infiltration is calculated using the Green-Ampt equation, which requires coefficients derived from the SWCC and the saturated hydraulic conductivity at various water table depths (Skaggs et al., 2012). The subsurface drainage represents the outflow from the underdrain in a bioretention cell. When the soil profile is saturated, and water is ponded on the surface, the model uses equations developed by Kirkham (1957) to estimate subsurface drainage rates. As drainage and evaporation continues, the water table starts to develop an approximately elliptical shape. For this condition, Kirkham's equation is no longer valid, and the model uses the steady-state Hooghoudt equation (van Schilfgaarde, 1974) to estimate subsurface drainage rates considering radial flow near the drains. The vertical seepage is calculated using Darcy's law and the Dupuit–Forchheimer assumptions (Skaggs et al., 2012) which uses the model seepage parameters: the piezometric head of the aquifer underneath the restrictive layer, the thickness of the restrictive layer, and the vertical hydraulic conductivity of the restrictive layer.

Lastly, the soil-water distribution in the profile is primarily determined by evapotranspiration and the depth of the root zone. When the moisture content of the soil in the root zone is greater than the wilting point, the ET is equal to potential evapotranspiration (PET) or maximum possible ET if sufficient water is available. PET can be estimated in the model using the temperature-based Thornthwaite method or user-defined PET can be entered to the model. If the ET is limited by the soil water conditions, then ET is equal to the upward flux of water as a function of the water table depth (which is determined from the SWCC). Water removed from profile through ET lowers the water table and changes the soil-water content in the unsaturated zone (Skaggs, 1991).

2.3.4 DRAINMOD Inputs

A brief description of model inputs is given in this section. DRAINMOD inputs are categorized into drainage design, soil, weather, and crop parameters. Inputs to the model can be found in Table 2.2. Calibration parameters are identified in this section but discussed in more detail in the calibration procedures (sections 2.6 and 2.7).

2.3.4.1 Drainage Design Inputs

The drainage design parameters of the model are primarily defined by site characteristics such as drainage configuration, underdrain diameter, drain depth from the surface, and ponding depth (Table 2.1). The similarities between the hydrologic components of DRAINMOD and bioretention cells can be observed in the two schematics in Figures 2.1 & 2.2. For further reference, Brown et al. (2013) created a table to show how each design parameter in DRAINMOD compared to features of a bioretention cell. The drainage coefficient defines the maximum drainage rate (cm/day) as limited by the hydraulic capacity of the drainage system. The initial value of the drainage coefficient was set to the maximum measured drainage rate. This value was further adjusted during model calibration to improve drainage predictions (Table 2.2). The drainage design parameters also include weir settings for modeling controlled drainage in agricultural applications (e.g. Youssef et al., 2018). These weir settings allow modeling of an IWS zone in a bioretention cell, a unique feature among models used for bioretention.

The vertical seepage parameters include the piezometric head of the aquifer, the thickness of the restricting layer, and the vertical conductivity of the restricting layer. The seepage parameters influence how much inflow is exfiltrated from the system versus how much leaves the cell via drainage or becomes overflow. The vertical conductivity of the restricting layer described the exfiltration rate into the underlying soil, which was estimated using the average drawdown rate (4.3 mm/hr; Table 2.1). The other seepage parameters were used as calibration parameters (Table 2.2).

2.3.4.2 Soil Inputs

Soil inputs were derived from the SWCC of the bioretention media and the saturated hydraulic conductivity (K_{sat}) of each layer. Each layer of the bioretention cell (mulch, bioretention media, sand, and gravel) was entered into the model as an individual soil layer. The saturated hydraulic conductivity (K_{sat}) was measured to be 17 cm/hr for the UC bioretention media. The K_{sat} of the sand layer was initially estimated at 15 cm/hr (Rawls et al., 1998; Domenico and Schwartz, 1990). The K_{sat} of the mulch and gravel layers were estimated at 50 and 200 cm/hr, respectively. Both the K_{sat} of the bioretention media and the sand layer were further adjusted during model calibration (Table 2.2).

2.3.4.3 Weather and Crop Inputs

DRAINMOD requires either daily or hourly precipitation, and minimum and maximum daily air temperatures, as inputs to the model. The model was set to calculate the daily PET using the Thornthwaite Method (Thornthwaite, 1948). The daily PET values estimated by the Thornthwaite method were adjusted by monthly correction factors ranging from 0.82–2.32 (Skaggs et al., 2012) to account for local conditions and remained the same as used by Winston (2015). The crop rooting depth was set to a constant 30 cm year-round due to the fact that seedlings were still establishing during the monitoring period although seasonal adjustments are available in the model.

Table 2.2 Comparison of calibrated parameters for the DRAINMOD (DM) and DRAINMOD-Urban (DM-Urban) models of the UC bioretention cell. Highlighted rows indicate calibration parameters.

Input Parameter	**Ursuline College (UC)** Initial Measured/ Estimated	DM	DM-Urban
System Design:			
Depth from soil surface to drain (cm)	107	107	107
Spacing between drains (cm)	597	597	597
Effective radius of drains (cm)	5	5	5
Actual distance from surface to impermeable layer (cm)	112.5	112.5	112.5
Drainage Coefficient (cm/day)*	25	120	300
Initial depth to water table (cm)	112.5	112.5	112.5
Maximum surface storage (cm) (aka ponding depth)	27.2	27.2	30
Kirkham's depth for flow to drains	1	1	1
Weir Settings:			
Bottom width of the ditch (cm)	0.01	0.01	1
Ditch side slope (H:V)	0.01	0.01	0.01
Weir Depth (cm)	52	52	52
Seepage:			
Piezometric head of aquifer (cm)*	53	23	12
Thickness of the restricting layer (cm)*	55	26.5	20
Vertical conductivity of restricting layer (cm/hr)	0.437	0.437	0.437
Lateral Saturated Conductivity:			
Layer 1: Mulch			
Bottom depth of layer (cm)	7.5	7.5	7.5
Saturated Hydraulic Conductivity (cm/hr)	50	50	50
Layer 2: Bioretention Media			
Bottom depth of layer (cm)	67.5	67.5	67.5
Saturated Hydraulic Conductivity (cm/hr)*	16	17	35
Layer 3: Choking Stone + Sand			
Bottom depth of layer (cm)	97.5	97.5	97.5
Saturated Hydraulic Conductivity (cm/hr)*	15	30	45
Layer 4: Gravel			
Bottom depth of layer (cm)	112.5	112.5	112.5
Saturated Hydraulic Conductivity (cm/hr)	200	200	200
Crop:			
Root Depth (year-round) (cm)	30	30	30

*DM-Urban calibration parameters

2.3.5 DRAINMOD Modifications

The code of the hydrologic component of DRAINMOD was modified by the model development team at North Carolina State University to better represent the rapid response time of an urban runoff hydrograph (shifting from hourly to sub-hourly inputs). In addition to concerns over the temporal resolution of the model, inflow estimations in the model were cumbersome and in need of improvement for urban stormwater applications. The original model provided a "Contributing Area Runoff" function that could be used to estimate the runoff from the drainage area as the input to the bioretention cell. However, this method required drainage area runoff to be calibrated to the bioretention cell inflow calculated with SWMM as mentioned above.

The inflow modeling was improved in DRAINMOD-Urban by permitting user-defined inputs. DRAINMOD-Urban requires two additional inputs: sub-hourly precipitation and sub-hourly inflow to the bioretention cell. Sub-hourly time steps are defined by the user ranging from one minute to an hour. This inflow file replaces the contributing runoff area file used in original DRAINMOD to provide more accurate estimation or measurement of the surface runoff entering the system. For example, instead of calibrating the model to the SWMM-calculated inflow, the inflow from SWMM was used as a direct input to the model. Depending on the level of measured data available, inflow can be entered directly or estimated by the user's preferred method providing more flexibility and eliminating the inflow calibration step (for more information on inflow modifications, see supplementary data).

The infiltration, drainage (outflow), runoff (overflow), ET, and seepage (exfiltration) outputs have also been modified at sub-hourly intervals. These output terms represent the terminology used by DRAINMOD while those in parentheses are corresponding terms common to the bioretention field. For the remainder of this paper, the term drainage refers to flow through the underdrain, and overflow will refer to surface runoff leaving the ponding zone of the bioretention cell. The improved temporal scale of the outputs can be used to examine the hydrograph of each water balance component, which was not possible in the previous applications of DRAINMOD to bioretention cells. As DRAINMOD-Urban was tested through calibration of the UC cell (described below), model behavior and programming were inspected and appropriate adjustments to the model were made.

2.3.6 Original DRAINMOD Calibration Procedure

Winston et al. (2016) found that 34 out of 50 storm events (68%) produced no drainage or overflow (i.e., were completely captured) at UC over a 7-month monitoring period. Events that produced drainage for multiple days were combined to compare with daily outputs from the original DRAINMOD model. For this study, only events with both measured and predicted flows were evaluated for a better comparison to individual hydrographs created by DRAINMOD-Urban. A total of 12 measured storm events produced drainage (herein referred to as “drainage events”) and four storm events produced overflow (referred to as “overflow events”).

The original DRAINMOD was parameterized based on the known design configuration and characteristics of the UC cell described by Winston (2015) & Winston et al. (2016) and listed in Table 2.1. The model parameters that could not be measured, such as the piezometric head of the contributing aquifer and thickness of the restricting layer, were used as calibration parameters. K_{sat} was measured at UC but measured K_{sat} values have been shown to vary widely up to three orders of magnitude with associated high skewness (Papanicolaou et al., 2015; Gwenzi et al., 2011; Warrick and Nielsen, 1980). It is also reasonable to use K_{sat} as a calibration parameter due to model sensitivity to this parameter (Winston, 2015; Skaggs et al., 2012; Brown, 2011). These parameters were changed to maximize the Nash-Sutcliffe Efficiency (NSE) parameter and minimize the percent error for the volumes across the 12 events that produced drainage and four events that produced overflow.

2.3.7 DRAINMOD-Urban Calibration Procedure

2.3.7.1 Top-Down and Bottom-Up Approaches

Top-down and bottom-up approaches have been examined in many hydrological and ecological studies (Hrachowitz and Clark, 2017; Bhave et al., 2014; Basu et al., 2011; Bai et al., 2009; Sivapalan and Young, 2006; Jarvis, 1993; Klemes, 1983). Often, these terms are used to describe model function and complexity, but here the terms are used to define the project-specific calibration strategy across temporal scales (Saraswat et al., 2015). "Top-down" has been described as capturing system behavior at a given spatial or temporal scale with limited model complexity then increasing the complexity by shifting to a smaller scale (Bai et al., 2009). The term "bottom-up" is generally defined as determining how a system may function at a given spatial or temporal scale based on its function at a smaller scale (Jarvis, 1993). In this study, the temporal scales were varied so that the top-down approach started with a broader temporal scale and moved to more specific, and the bottom-up approach began with a smaller temporal scale and moved to a coarser time step.

These two approaches were used to investigate the performance of DRAINMOD-Urban and compare its predictions to the original DRAINMOD (Figure 2.3). First, DRAINMOD was calibrated to find a satisfactory parameter set for modeling event volumes (taken from Winston, 2015). This parameter set (DM, Table 2.2) was then applied to DRAINMOD-Urban in a top-down approach. Next, DRAINMOD-Urban was calibrated to determine a new set of parameters capable of modeling hydrographs at a higher temporal resolution. This parameter set (DM-Urban, Table 2.2) was then utilized in the original DRAINMOD in a bottom-up approach.

For the initial assessment, the volume-calibrated design configuration and soil parameters used for the original DRAINMOD simulation of the UC cell (taken from Winston, 2015) were utilized for the DRAINMOD-Urban simulation. The only difference in the inputs for the improved DRAINMOD-Urban was the measured precipitation and inflow on a 1-minute interval. This process highlighted the impact of a more sensitive time resolution; essentially, can the model be downscaled successfully after calibration at a lower resolution (larger time step)? This is referred to as the top-down approach because the model is first calibrated with a longer temporal scale, then downscaled to a shorter temporal scale (Figure 2.3).

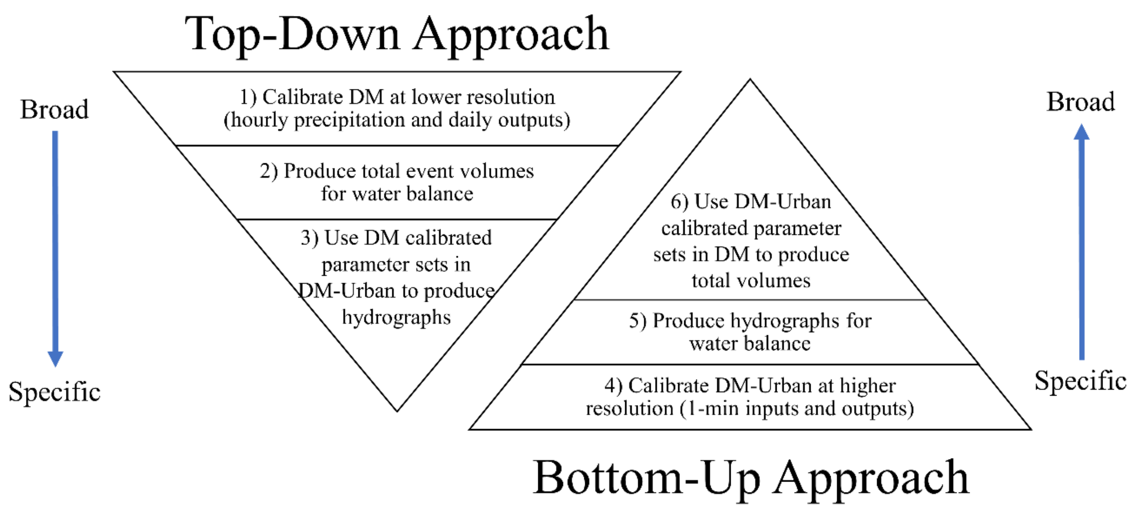


Figure 2.3 Top-down (steps 1-3) and bottom-up (steps 4-6) approaches to volume and hydrograph calibrations. The top-down approach moves from broad to specific and the bottom-up approach from specific to broad. DM refers to DRAINMOD and DM-Urban refers to DRAINMOD-Urban.

Next, the hydrograph-calibration process with DRAINMOD-Urban was performed at a higher resolution (i.e., 1-minute time step). Parameters that were difficult to measure such as the drainage coefficient, saturated hydraulic conductivity, piezometric head of the aquifer, and thickness of the restricting layer were adjusted in DRAINMOD-Urban to optimize the chosen model performance statistics. The extensive output files were entered into a macro-enabled Excel spreadsheet to separate into storm events with drainage or overflow, create hydrographs for modeled and measured data and calculate statistical metrics. Next, the bottom-up approach was applied: the new parameters used to match hydrographs in the DRAINMOD-Urban calibration were applied to the original DRAINMOD. Volumes for the entire water balance were compared among DRAINMOD and DRAINMOD-Urban parameter sets.

2.3.7.2 Measuring DRAINMOD-Urban Performance

Legates and McCabe (1999) recommend choosing one goodness-of-fit test and one absolute error measure with additional supporting information to fully assess model performance. Moriasi et al. (2007) breaks performance statistics into three categories: (1) standard regression [Pearson's correlation coefficient (r) and the coefficient of determination (R^2)]; (2) dimensionless goodness-of-fit [index of agreement (d), Nash-Sutcliffe efficiency (NSE or E), and the respective relative error counterparts (d_1 and E_1)]; and (3) absolute error index [mean absolute error (MAE), mean squared error (MSE), root-mean-squared error (RMSE), percent bias (PBIAS), and the RMSE-observations standard deviation (RSR)] statistics. Of these statistics, the NSE and PBIAS are widely reported in research leading to more clearly defined performance ranges to determine if model performance is satisfactory (Moriasi et al., 2007). In fact, Skaggs et al. (2012) suggested acceptable, good and excellent ranges of NSE for drainage in DRAINMOD dependent on the temporal scale of the outputs (daily, monthly, or annually). Thus, the cumulative NSE and PBIAS for all drainage and overflow events were optimized to find the hydrograph-calibrated parameter set.

Two sets of statistics were generated during the calibration. First, the cumulative statistics were calculated by combining all events end to end (without inter-event periods) to determine a single NSE value for each simulation. This was important since NSE and PBIAS fluctuated for each event due to the variability in hydrologic behavior based on storm size, duration, and intensity, as well as antecedent moisture content of the soil. Next, NSE was calculated as a continuous metric which included all inter-event periods to show how well the model predicts drainage and overflow across the entire simulation period. The continuous NSE was found to be higher than the cumulative NSE due to its ability to accurately predict periods of no drainage or overflow. Following calibration, additional statistics mentioned above were calculated for a more complete analysis of model performance. A visual assessment of each drainage and overflow hydrograph was also performed. Visual graphical techniques are recommended to identify model bias and differences in the shape of the hydrograph, including timing and magnitude of peak flows (Moriasi et al., 2007; Legates and McCabe, 1999). Finally, the hydrographs of the calibrated model were also quantitatively evaluated using parameters such as the storm duration, time to peak, and peak flow. In storms with multiple peaks, these measures were based on the largest peak.

2.4 Results and Discussion

2.4.1 Original DRAINMOD Model Performance

The calibrated DRAINMOD model produced high NSE values, 0.83 for drainage and 0.57 for overflow for the UC bioretention cell. These values suggest excellent (or very good) performance of the model (for a perfect model fit, NSE=1) when comparisons of modeled versus measured data are based on daily event volumes of drainage (Skaggs et al., 2012; Moriasi et al., 2007). Overflow was categorized as acceptable performance according to Skaggs et al. (2012) and satisfactory according to Moriasi et al., (2007).

2.4.2 Top-Down Approach: Volume to Hydrograph

To test the model's ability to predict hydrology at a finer scale (1-minute versus daily), the output from DRAINMOD-Urban (using the DRAINMOD calibration parameters) was compared to the observed drainage and overflow hydrographs. Although the calibrated DRAINMOD model showed excellent performance at the daily time scale, using these calibration parameters in DRAINMOD-Urban resulted in poor performance for predicting 1-minute resolution hydrographs (Figure 2.4). The individual DRAINMOD-Urban event NSEs ranged from -1.74 to 0.56 with a cumulative NSE of 0.31 for drainage, and a range of -56.5 to -0.64 and a cumulative -1.82 NSE for overflow. The PBIAS was also high, ranging from ±5 to ±246 for drainage (cumulative PBIAS=16.7) and from ±33 to ±539 for overflow (cumulative PBIAS= -96.8). These statistics and visual assessment of the hydrographs indicated that, following the top-down approach, the model was not satisfactorily downscaled. These results suggested that further calibration of the model was needed as there were fine-scale processes not well-represented by the model parameters (Baffaut et al., 2015).

Although it is expected to find reduced model performance at smaller time-steps, a visual evaluation of the predicted hydrographs also indicated poor performance (Engel and Hoonhout, 2007; Moriasi et al., 2007). Some drainage events showed a lack of correlation with the timing and duration of the event while others showed discrepancies in volume and peak flow rates. Many events were affected by restricted drainage capacity, which caused a plateau effect (Figure 2.4a). Reasonable prediction of overflow timing was observed for

DRAINMOD-Urban, but much higher peak flows were modeled than measured (Figure 2.4b).

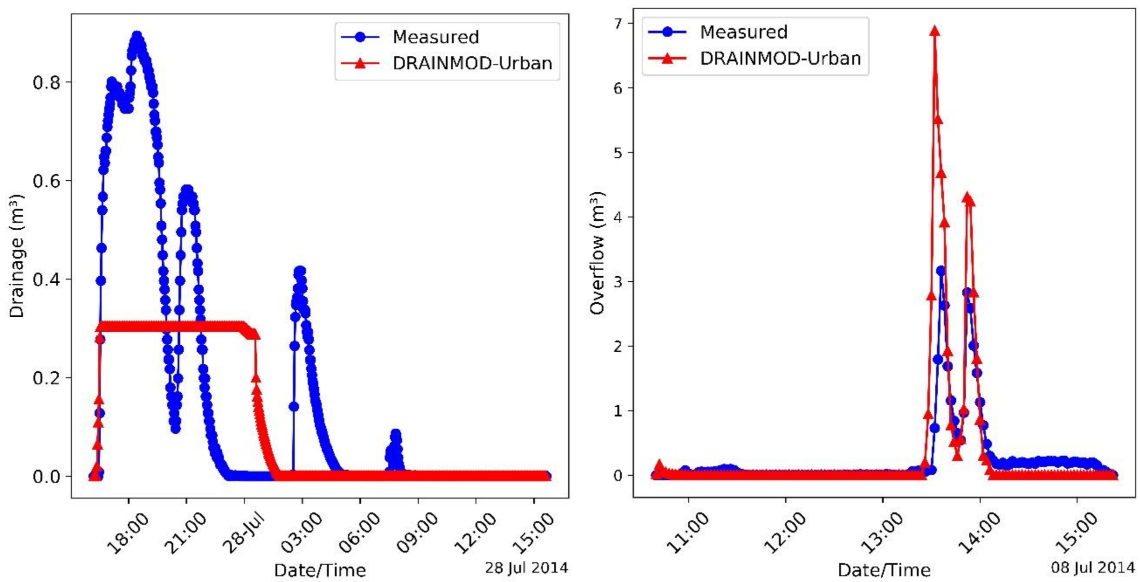


Figure 2.4. a) Example of a drainage hydrograph that has overestimated event duration as well as restricted drainage creating a plateau effect and underestimated volume predicted by DRAINMOD-Urban b) Example of an overflow hydrograph that shows good correspondence with duration and time to peak but DRAINMOD-Urban overestimated the flow volume and peak flow rate. Modeled outputs were created using a top-down approach.

2.4.3 DRAINMOD-Urban Model Performance

2.4.3.1 Performance Summary

Due to the poor performance of DRAINMOD-Urban using calibration parameters developed in the lower resolution DRAINMOD model, additional calibration was performed to define an adequate parameter set for producing modeled hydrographs similar to those measured. Calibration parameters were adjusted in DRAINMOD-Urban until improvement in hydrograph peak flow, timing, and duration were visually evident (Figure 2.5). The individual event NSEs for drainage hydrographs ranged from -1.75 to 0.80 with a cumulative NSE of 0.60. For overflow hydrographs, event NSEs ranged from -1.59 to 0.74 and cumulative NSE=-0.10 (Table 2.4). The continuous NSE values (that included inter-event periods) were calculated as NSE=0.68 for drainage and NSE=-0.04 for overflow. The NSE values in this study indicate a good fit between measured and modeled drainage data, especially given the fine temporal scale (Moriasi et al., 2007). Skaggs et al. (2012) suggested performance ranges of NSE for DRAINMOD suggests that an NSE=0.60 would be considered “good” performance at a daily scale (and likely better performance at a smaller time scale). The PBIAS was reduced from the initial assessment, ranging from ±5 to ±181 for drainage (cumulative PBIAS= 5.2) and from ±15 to ±60 for overflow (cumulative PBIAS= -18.5). The recommended PBIAS varies depending on the constituent evaluated, but for streamflow, PBIAS< ±10 indicated “very good” performance and ±15<PBIAS< ±25 is considered “satisfactory” (Moriasi et al., 2007).

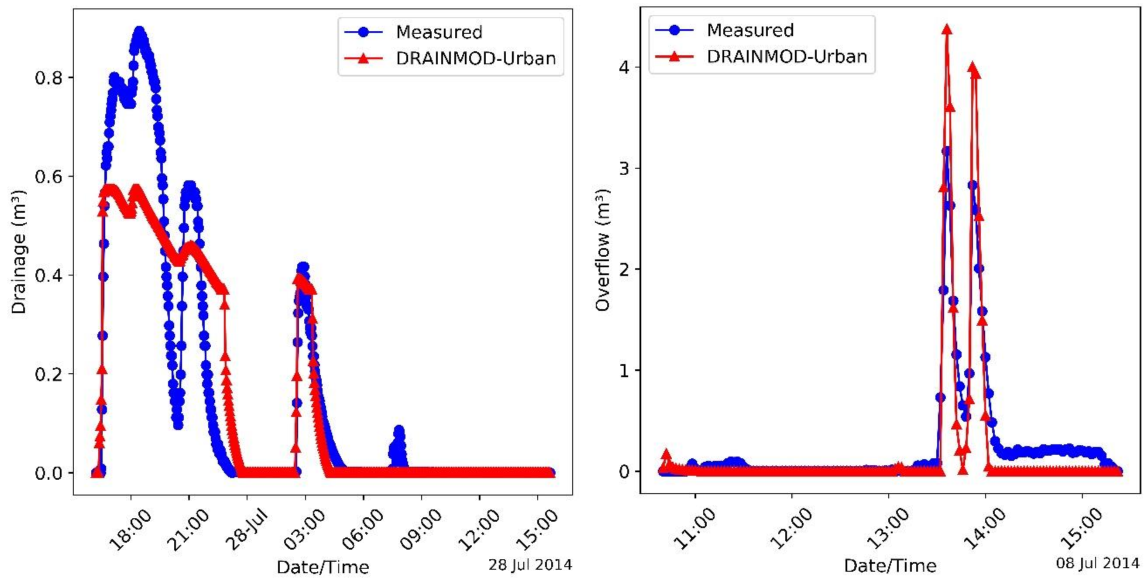


Figure 2.5 a) Example of a drainage hydrograph that has good correlation of modeled and measured data with respect to event duration, peak flows and flow volume (compare with Figure 2.4a); b) Example of an overflow hydrograph that shows good correspondence with duration and time to peak and improved peak flows (compare with Figure 2.4b)

2.4.3.2 Statistical Analysis

The DRAINMOD-Urban model was accessed using a robust multi-criteria method. Notably, the effect of the squared terms in the NSE can be reduced to give proper weighting to errors using a modified goodness-of-fit statistic (E_1). E_1 for drainage appeared smaller than the NSE for drainage (as expected by Legates and McCabe, (1999)), but the E_1 for overflow was larger than the NSE for overflow (Table 2.3). This was because there are a large number of small values in the tails of the overflow hydrographs and a sharp peak as opposed to drainage hydrographs which have much larger volumes and smoother shapes. These small values lower the observed mean used in the denominator of the NSE calculation. When the denominator is squared, it leads to a decreased NSE. It is therefore suggested that for small overflow events, the E_1 parameter should be considered for model evaluation instead of the traditional NSE.

Unsurprisingly, the correlation parameters (r and R^2) did not fit this model well. The large standard deviation for drainage and overflow at a 1-minute timestep in addition to the natural shape of a hydrograph caused large scatter, which decreased the correlation between the modeled and measured values (Table 2.3). The error indices presented very low error in the model with the highest error coming from the RMSE, which had the same conflict of squared terms as the NSE. The index of agreement (d) showed very good results with a value of 0.93 for drainage and 0.68 for overflow (with an optimal value of 1). Like the case with E_1, for drainage, d was greater than d_1 as expected by Legates and McCabe (1999), but for overflow, d was less than d_1 though it still reached satisfactory model performance.

Table 2.3 Additional correlation, error index, and goodness-of-fit (GOF) statistics calculated for the final calibration of DRAINMOD-Urban.

	Observed		**Predicted**		**Correlation**		**Error Index Statistics**					**GOF**		**Modified GOF**	
	μ	**σ**	**μ**	**σ**	**r**	**R^2**	**MAE**	**MSE**	**RMSE**	**RSR**	**PBIAS**	**d**	**E**	**d_1**	**E_1**
Perfect fit					**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**1**	**1**
Drainage	0.10	0.15	0.08	0.12	0.42	0.18	0.005	0.100	0.316	0.034	5.19	0.93	0.60	0.75	0.52
Overflow	0.08	0.26	0.10	0.44	0.73	0.54	-0.015	0.202	0.450	0.059	-18.5	0.68	-0.10	0.74	0.36

2.4.3.3 Model Performance Analysis

The NSE calculated for each event (Table 2.4) provided the opportunity to investigate patterns among event performance in the model. Drainage results showed patterns in performance among volume, peak flow, and timing/duration. From this dataset, storm intensity, rainfall duration, and antecedent dry period did not appear to influence the NSE of a drainage event. Overflow model performance related to each of these features is described, but more overflow events are needed to verify these observations.

Table 2.4 Nash-Sutcliffe Efficiency (NSE) and percent bias (PBIAS) for all drainage and overflow events evaluated including the average and cumulative values. Dashes represent storms that did not produce overflow. Event 5 also did not produce drainage in the model, and therefore, statistics were not calculated.

	DRAINAGE		OVERFLOW	
Event #	NSE	PBIAS	NSE	PBIAS
1	0.40	-29	-	-
2	0.34	43	-0.10	-42
3	-1.75	-83	-	-
4	0.65	5	0.74	20
5	-	-	-	-
6	0.80	5	-1.59	-15
7	0.58	-6	-	-
8	-0.97	-131	-	-
9	0.39	-30	-	-
10	0.63	28	-0.59	-60
11	-0.82	-181	-	-
12	0.68	-8	-	-
Cumulative	0.60	5.19	-0.10	-18.5

2.4.3.4 Drainage Volume

Drainage event volumes from DRAINMOD-Urban were compared to measured data and those modeled using the original DRAINMOD (Table 2.5). The event volumes predicted by DRAINMOD-Urban were often closer to measured drainage volumes than the event volumes modeled with the original DRAINMOD. The cumulative drainage from DRAINMOD and DRAINMOD-Urban were very similar to measured volumes, approximately 6-13% error (Table 2.5). The percent error for cumulative drainage predicted by DRAINMOD-Urban was better than that predicted by DRAINMOD, even though DRAINMOD was calibrated to best match predicted and measured volumes of each water balance component. Therefore, DRAINMOD-Urban does not lose accuracy in modeling drainage volumes but simply adds the benefits of hydrograph production relative to DRAINMOD.

The drainage events with the smallest measured volumes (<15 m^3) had the worst NSE values (these events corresponded to rainfall less than 25 mm). In this case, the small drainage events behave similarly to the small overflow hydrographs described above such that there are more small drainage volumes at the tails of the hydrograph and when those are squared in the denominator of the NSE, the metric itself declines. Most of the events that performed well (NSE> 0.5) had differences in measured and modeled drainage volumes <6 m^3. This is exceptional performance from a volume perspective, so it is expected that improvement in the prediction of hydrograph timing, duration, and peak flow would further improve NSE for these events.

There were three events (1, 9, & 10) that had similar measured drainage (57-65 m^3) and the model predicted within 19 m^3 for each event with two overpredicting volume (NSE=0.39 and 0.40) and one underpredicting (NSE=0.63). The differences in performance of these events despite similar rainfall and drainage characteristics are related to longer drainage duration predicted by the model seen in Events 1 and 9 (differences in timing and duration are discussed more below). Event 10 did not have duration mismatch, but the model did not pick up the second peak which reduced the drainage predicted, leading to the underestimation of volume. The evaluation of these events shows that the total volume difference does not affect the NSE as much as the difference of volume at each time step (which is larger with timing and duration errors).

2.4.3.5 Drainage Peak Flow

Hydrograph examination showed that peak flow for drainage was overestimated by DRAINMOD-Urban for 3 of the 12 storms with the maximum difference equal to 3.7 L/s (Table 2.6). Based on visual observation of the drainage hydrographs, in events (3, 8, 11, & 12) with the worst NSE values, DRAINMOD-Urban overpredicted the peak flow. The exception is Event 12 which was only overestimated for the smaller, first of two peaks. Although these events all had overestimated peak drainage, the magnitude of the difference in measured and modeled peaks varied. In fact, in all drainage events, the difference in modeled and measured peak flow ranged from 0.4-3.7 L/s yet there was no pattern detected to explain changes in peak magnitude prediction from event to event.

2.4.3.6 Drainage Timing and Duration

The difference in modeled and measured drainage duration varied from two to 42 minutes for shorter events (less than 15-hour precipitation duration) and up to a 9-hour difference for longer events (greater than 15 hours of precipitation) (Table 2.6). From visual analysis, the drainage events with the best NSE values ($NSE>0.5$) had better prediction of timing and duration. DRAINMOD-Urban accurately represented the rising limb of the hydrographs for most events, but extended duration of drainage predicted by DRAINMOD-Urban contributed to inaccurate falling limbs compared to measured. Drainage events that performed in the mid-range of NSE values ($0.3<NSE<0.4$) showed some duration mismatch. Although the drainage duration could be predicted longer than measured, the modeled drainage time to peak varied no more than one hour from the measured hydrograph. In fact, half of the events were within 18 minutes of the measured hydrograph (Table 2.6).

Table 2.5 Volumes of drainage and overflow per storm event for measured, DRAINMOD-Urban (DM-Urban), and original DRAINMOD (DM). Inflow from DM came from the Contributing Area Runoff function and daily outputs were combined for multi-day events. Inflow from DM-Urban was calculated in SWMM on a minute basis.

		Inflow (m3)		Drainage (m3)					Overflow (m3)				
Event #	Rainfall (mm)	DM-Urban	DM	Measured	DM-Urban	% Error	DM	% Error	Measured	DM-Urban	% Error	DM	% Error
1	42.7	134	142	56.5	73.0	29	73.0	29	0.0	0.0	-	0.0	-
2	89.2	297	310	195	112	-43	164	-16	51.8	73.6	42	55.9	8.0
3	10.4	50.7	-	4.5	8.2	83	-	-	0.0	0.0	-	-	-
4	45	152	212	84.7	80.6	-5	103	11	34.0	27.1	-20	36.4	7.3
5	5.1	15.0	-	4.2	0.0	-100	-	-	0.0	0.0	-	-	-
6	70.1	222	235	114	108	-5	97.8	-14	40.1	46.1	15	68.2	70
7	32	97.9	135	50.2	53.1	6	69.4	38	0.0	0.0	-	7.1	-
8	28.2	83.0	90.7	14.8	34.2	131	45.1	205	0.0	0.0	-	0.0	-
9	42.4	129	141	62.7	81.3	30	77.9	24	10.4	0.0	-100	12.3	18
10	48.3	150	155	64.6	46.5	-28	77.7	20	-	-	-	-	-
11	20.8	61.1	50.0	6.4	18.1	181	15.1	135	0.0	0.0	-	0.0	-
12	25.4	77.9	123	35.8	38.7	8	59.0	65	0.0	0.0	-	4.2	-
SUM	488	1470	1594	693	653	-6	782	13	136	147	8	184	35

2.4.3.7 Overflow

Overflow event volumes from DRAINMOD-Urban were compared to those measured and those modeled in DRAINMOD (Table 2.5). The cumulative overflow volume improved significantly in DRAINMOD-Urban from a 47% error to only 9.8% error. However, some of the event volumes were better predicted by DRAINMOD.

Peak flow was overestimated by DRAINMOD-Urban for all overflow events with the maximum difference equal to 28.8 L/s (Table 2.7). The differences in peak flow are much larger for overflow than for drainage, which is apparent from visual analysis of the hydrographs. The NSE was noticeably smaller for overflow events, and examination of the hydrographs still shows overestimation of peak flows by DRAINMOD-Urban although the peaks improved with calibration. It is important to note that the NSE parameter emphasizes matching the peak of the hydrograph (Tian et al., 2016; Krause et al., 2005; Legates and McCabe, 1999). Therefore, small overflow events can match the timing and duration well, but the overestimated peak drastically affects the NSE statistic. If the exponent in the squared terms are reduced, such as the modified goodness-of-fit statistics (d_1 and E_1), there is less emphasis on errors due to low flows and the statistical measures better replicate low flows in addition to the peak flows (Tian et al., 2016; Legates and McCabe, 1999).

The overflow hydrographs visually showed good agreement for time to peak and duration between the modeled and measured overflow events. The difference in duration of overflow ranged from 10 minutes to 2.8 hours at the maximum. The time to peak was precisely the same for all overflow events (Table 2.7).

The small number of overflow events evaluated in this study is not suitable for linking performance and storm characteristics. However, some overflow performance could be explained by the same patterns seen in the drainage events. For example, Event 10 had the smallest measured overflow volume (5.6 m^3) and poor performance (NSE= -0.59) as seen in most small drainage events. Similarly, Event 4, which had the best performance of the overflow events (NSE=0.74), had excellent timing.

Table 2.6 Analysis of drainage hydrographs created by DRAINMOD-Urban (DM-Urban) and measured drainage.

	Peak Flow (L/s)			Time to Peak (hr)			Event Duration (hr)			
Event #	Measured	DM-Urban	Diff.	Measured	DM-Urban	Diff. (min)	Measured	DM-Urban	Diff. (hr)	Diff. (min)
1	8.0	4.8	-3.3	2.1	1.9	-12	15.1	14.8		-18
2	8.4	4.8	-3.7	5.2	4.5	-44	19.1	9.7	-9.4	
3	2.2	3.2	1.1	1.2	0.9	-16	3.0	2.3		-42
4	6.8	4.8	-2.0	4.2	3.3	-54	7.8	7.4		-24
6	7.5	4.8	-2.7	2.2	2.2	-4	17.2	12.1	-5.1	
7	5.7	3.7	-2.0	2.5	2.5	0	5.9	6.2		18
8	2.7	3.2	0.5	9.1	9.1	-2	11.1	11.1		2
9	6.3	4.8	-1.5	1.7	1.3	-28	6.2	6.4		8
10	5.2	4.8	-0.4	2.3	1.8	-28	11.2	4.8	-6.3	
11	2.4	3.1	0.7	5.8	5.7	-8	11.0	6.9	-4.1	
12	4.0	3.6	-0.4	3.9	3.6	-18	6.6	5.9		-42

Table 2.7 Analysis of overflow hydrographs created by DRAINMOD-Urban (DM-Urban) and measured overflow

	Peak Flow (L/s)			Time to Peak (hr)			Event Duration (hr)			
Event #	Measured	DM-Urban	Diff.	Measured	DM-Urban	Diff. (min)	Measured	DM-Urban	Diff. (hr)	Diff. (min)
2	44.0	66.1	22.0	1.7	1.7	0.0	6.0	4.5	-1.5	-88
4	26.4	36.5	10.1	2.9	2.9	0.0	4.7	3.4	-1.3	-78
6	21.1	49.9	28.8	0.7	0.7	0.0	5.0	2.2	-2.8	-168
10	12.8	31.9	19.2	0.6	0.6	0.0	0.9	0.7	-0.2	-10

2.4.4 Bottom-Up Approach: Hydrograph to Volume

As noted above, the bottom-up approach involved scaling up from the DRAINMOD-Urban temporal resolution to that of the original DRAINMOD using the calibration parameters developed at the 1-minute data resolution. Following hydrograph calibration in DRAINMOD-Urban, the calibrated input parameters (DM-Urban, Table 2.2) were entered in DRAINMOD to assess the event volumes produced at a daily time step using the bottom-up approach. For comparison, the percent error and NSE were calculated for the two parameter sets (DM and DM-Urban from Table 2.2) used in the original DRAINMOD (Table 2.8). For drainage, the performance of the DRAINMOD-Urban parameters declined slightly with a larger percent error but remained the same NSE. For overflow, the percent error and NSE both improved with the DRAINMOD-Urban parameters. This indicates that while the top-down calibration approach was unsuccessful (as noted above), the bottom-up approach provided nearly the same or better results as those reported by calibrating the original DRAINMOD at a daily time step. In short, calibration parameters developed by DRAINMOD do not produce acceptable hydrographs when analyzed at a higher resolution in DRAINMOD-Urban. Conversely, calibration parameters from DRAINMOD-Urban can be used in a lower resolution (daily) DRAINMOD with minimal loss of performance (in comparison to merely calibrating DRAINMOD volumes at a daily resolution).

Table 2.8 Bottom-up analysis: Parameter sets from DRAINMOD and DRAINMOD-Urban calibrations (refer to Table 2.2) are both used in the DRAINMOD (DM) model to compare event and total volumes of drainage and overflow and Nash-Sutcliffe Efficiency (NSE)

				Measured		DRAINMOD Parameters-Volume Calibration				DRAINMOD-Urban Parameters-Hydrograph Calibration			
Storm Event Start Date	**Event #**	**Rainfall (mm)**	**DM Inflow (m^3)**	**Drainage (m^3)**	**Overflow (m^3)**	**Drainage (m^3)**	**% Error**	**Overflow (m^3)**	**% Error**	**Drainage (m^3)**	**% Error**	**Overflow (m^3)**	**% Error**
6/18/2014	1	42.9	142	56.5	0.0	73.0	29	0.0	-	70.4	25	0.0	-
6/24/2014	2	97.0	310	195	51.8	164	-16	55.9	8	189	-3	27.1	-48
7/7/2014	3	17.3	-	4.5	0.0	-	-	-	-	-	-	-	-
7/8/2014	4	45.0	212	84.7	34.0	103	11	36.4	7	111	19	21.1	-38
7/9/2014	5	5.1	-	4.2	0.0	-	-	-	-	-	-	-	-
7/27/2014	6	86.1	235	114	40.1	97.8	-14	68.2	70	121	6	41.6	4
8/12/2014	7	46.2	135	50.2	0.0	69.4	38	7.1	-	71.1	42	3.0	-
8/19/2014	8	28.2	90.7	14.8	0.0	45.1	205	0.0	-	52.0	251	0.0	-
9/5/2014	9	42.4	141	62.7	10.4	77.9	24	12.3	18	85.8	37	0.0	-100
9/10/2014	10	48.3	155	64.6	5.6	77.7	20	-	-	88.2	37	-	-
10/3/2014	11	20.8	50.0	6.4	0.0	15.1	135	0.0	-	18.5	187	0.0	-
10/15/2014	12	39.6	123	35.8	0.0	59.0	65	4.2	-	64.1	79	0.8	-
TOTAL		**519**	**1594**	**693**	**142**	**782**	**13**	**184**	**30**	**871**	**26**	**93**	**-34**
NSE						**0.83**		**0.57**		**0.83**		**0.66**	

2.5 Conclusions

When calibration parameters generated using DRAINMOD (daily outputs, NSE = 0.83, PBIAS = 0.57) were evaluated with DRAINMOD-Urban at a 1-minute time step (top-down approach), errors in hydrograph duration, shape, and peak flows were exhibited in addition to lower model performance metrics (drainage NSE=0.31, PBIAS=16.7). This comparison indicated that the model required further hydrograph calibration to improve DRAINMOD-Urban performance and accurately represent measured hydrographs. NSE values for the hydrographs from DRAINMOD-Urban were promising (drainage NSE=0.60, PBIAS=5.2) given the complexity of bioretention system hydrology and the high temporal resolution. This outcome was supported by both statistical standards and visual assessment of volume, peak flow, timing, and duration of each hydrograph. When the calibration parameters for this enhanced DRAINMOD-Urban model were utilized in the lower resolution DRAINMOD model (bottom-up approach), the results were excellent, showing improved performance over the original DRAINMOD parameters calibrated to total volumes.

This study shows the strong influence of scale in model performance. When a very accurate long-term continuous simulation bioretention model was disaggregated to a finer time scale, performance suffered if calibration parameter sets were not updated. When long-term water balances are desired, this is not critical but becomes essential when accurate drainage hydrographs are desired. Example applications include understanding storm-specific performance or understanding how bioretention functions when combined at the watershed scale, that is, when there is a need to understand how individual site scale hydrographs are combined at the system level. Furthermore, drainage and overflow hydrographs could be useful for understanding effects on hydrology, and other stormwater controls downstream of the bioretention cell (Heasom et al., 2006). DRAINMOD-Urban has demonstrated strong potential for modeling hydrographs that accurately predict measured data.

More studies need to be conducted with larger datasets to improve statistical conclusions, especially for overflow events. Future work can be performed to analyze the sensitivity of calibration and other input parameters in DRAINMOD-Urban, especially soil parameters that currently require extensive laboratory testing. DRAINMOD-Urban also needs to be compared to other common bioretention models with respect to representation of fundamental hydrologic processes. A discussion of whether the complexity of inputs required by DRAINMOD-Urban leads to improved accuracy or if models with simpler inputs can provide similar results is warranted (e.g., particularly for planning exercises). Ultimately, DRAINMOD-Urban is well-suited to modeling the flashy nature of urban bioretention while considering the influence of antecedent soil moisture, underdrain configuration, and unsaturated flow conditions in the media.

2.6 References

Baffaut, C., M. Dabney, S., D. Smolen, M., A. Youssef, M., V. Bonta, J., L. Chu, M., A. Guzman, J., S. Shedekar, V., K. Jha, M. and G. Arnold, J. (2015) Hydrologic and Water Quality Modeling: Spatial and Temporal Considerations. Transactions of the ASABE 58(6), 1661-1680. https://doi.org/https://doi.org/10.13031/trans.58.10714

Bai, Y., Wagener, T. and Reed, P. (2009) A Top-Down Framework for Watershed Model Evaluation and Selection under Uncertainty. Environmental Modelling & Software 24(8), 901-916. https://doi.org/10.1016/j.envsoft.2008.12.012

Barbu, I.A. and Ballestero, T.P. (2015) Unsaturated Flow Functions for Filter Media Used in Low-Impact Development—Stormwater Management Systems. Journal of Irrigation and Drainage Engineering 141(1), 04014041. https://doi.org/10.1061/(asce)ir.1943-774.0000766

Basu, N.B., Thompson, S.E. and Rao, P.S.C. (2011) Hydrologic and Biogeochemical Functioning of Intensively Managed Catchments: A Synthesis of Top-Down Analyses. Water Resources Research 47. https://doi.org/Artn W00j1510.1029/2011wr010800

Bhave, A.G., Mishra, A. and Raghuwanshi, N.S. (2014) A Combined Bottom-up and Top-Down Approach for Assessment of Climate Change Adaptation Options. Journal of Hydrology 518, 150-161. https://doi.org/10.1016/j.jhydrol.2013.08.039

Brown, R.A. (2011) Evaluation of Bioretention Hydrology and Pollutant Removal in the Upper Coastal Plain of North Carolina with Development of a Bioretention Modeling Application in DRAINMOD. Doctoral dissertation, North Carolina State University, Raleigh, North Carolina.

Brown, R.A., Skaggs, R.W. and Hunt, W.F. (2013) Calibration and Validation of DRAINMOD to Model Bioretention Hydrology. Journal of Hydrology 486, 430-442. https://doi.org/10.1016/j.jhydrol.2013.02.017

Davis, A.P., Hunt, W.F., Traver, R.G. and Clar, M. (2009) Bioretention Technology: Overview of Current Practice and Future Needs. Journal of Environmental Engineering 135(3), 109-117. https://doi.org/10.1061//ASCE/0733-9372/2009/135:3/109

Dietrich, A., Yarlagadda, R. and Gruden, C. (2017) Estimating the Potential Benefits of Green Stormwater Infrastructure on Developed Sites Using Hydrologic Model Simulation. Environmental Progress & Sustainable Energy 36(2), 557-564. https://doi.org/10.1002/ep.12428

Domenico, P.A. and Schwartz, F.W. (1990) Physical and Chenical Hydrogeology, John Wiley and Sons, New York.

Elliott, A. and Trowsdale, S. (2007) A Review of Models for Low Impact Urban Stormwater Drainage. Environmental Modelling & Software 22(3), 394-405. https://doi.org/10.1016/j.envsoft.2005.12.005

Engel, J. and Hoonhout, H.C.M. (2007) Statistics Development: Statistical Methods Meeting the User's Needs. Asta-Advances in Statistical Analysis 91(4), 413-427. https://doi.org/10.1007/s10182-007-0046-x

Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P.S., Rivard, G., Uhl, M., Dagenais, D. and Viklander, M. (2014) SUDS, LID , BMPs, WSUD and More – the Evolution and Application of Terminology Surrounding Urban Drainage. Urban Water Journal 12(7), 525-542. https://doi.org/10.1080/1573062x.2014.916314

Guo, J.C.Y. and Luu, T.M. (2015) Hydrologic Model Developed for Stormwater Infiltration Practices. Journal of Hydrologic Engineering 20(9), 06015001. https://doi.org/10.1061/(asce)he.1943-5584.0001161

Gwenzi, W., Hinz, C., Holmes, K., Phillips, I.R. and Mullins, I.J. (2011) Field-Scale Spatial Variability of Saturated Hydraulic Conductivity on a Recently Constructed Artificial Ecosystem. Geoderma 166(1), 43-56. https://doi.org/10.1016/j.geoderma.2011.06.010

Hathaway, J.M., Brown, R.A., Fu, J.S. and Hunt, W.F. (2014) Bioretention Function under Climate Change Scenarios in North Carolina, USA. Journal of Hydrology 519, 503-511. https://doi.org/10.1016/j.jhydrol.2014.07.037

Heasom, W., Traver, R.G. and Welker, A.L. (2006) Hydrologic Modeling of a Bioinfiltration Best Management Practice. Journal of the American Water Resources Association 42(5), 1329-1347.

Hrachowitz, M. and Clark, M.P. (2017) Hess Opinions: The Complementary Merits of Competing Modelling Philosophies in Hydrology. Hydrology and Earth System Sciences 21(8), 3953-3973. https://doi.org/10.5194/hess-21-3953-2017

Jarvis, P.G. (1993) Scaling Physiological Processes: Leaf to Globe. J.R., E. and C.B., F. (eds), Academic Press.

Kaykhosravi, S., Khan, U. and Jadidi, A. (2018) A Comprehensive Review of Low Impact Development Models for Research, Conceptual, Preliminary and Detailed Design Applications. Water 10(11), 1541. https://doi.org/10.3390/w10111541

Kirkham, D. (1957) Drainage of Agricultural Lands. Luthin, J.N. (ed), pp. 139-181, ASA, Madison, WI.

Klemes, V. (1983) Conceptualization and Scale in Hydrology. Journal of Hydrology 65(1-3), 1-23. https://doi.org/Doi 10.1016/0022-1694(83)90208-1

Kottek, M., Grieser, J., Beck, C., Rudolf, B. and Rubel, F. (2006) World Map of the Köppen-Geiger Climate Classification Updated. Meteorologische Zeitschrift 15(3), 259-263.

Krause, P., Boyle, D.P. and Base, F. (2005) Comparison of Different Efficiency Criteria for Hydrological Model Assessment. Advances in Geosciences, 5, 89-97.

Lee, R.S., Traver, R.G. and Welker, A.L. (2013) Continuous Modeling of Bioinfiltration Storm-Water Control Measures Using Green and Ampt. Journal of Irrigation and Drainage Engineering 139(12), 1004-1010. https://doi.org/10.1061/(asce)ir.1943-4774.0000651

Legates, D.R. and McCabe, G.J. (1999) Evaluating the Use of "Goodness-of-Fit" Measures in Hydrologic and Hydroclimatic Model Validation. Water Resources Research 35(1), 233-241. https://doi.org/Doi 10.1029/1998wr900018

Liu, J., Sample, D., Bell, C. and Guan, Y. (2014) Review and Research Needs of Bioretention Used for the Treatment of Urban Stormwater. Water 6(4), 1069-1099. https://doi.org/10.3390/w6041069

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L. (2007) Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Transactions of the ASABE 50(3), 885-900. <Go to ISI>://WOS:000248036800021

Negm, L.M., Youssef, M.A., Skaggs, R.W., Chescheir, G.M. and Kladivko, E.J. (2014) DRAINMOD-Dssat Simulation of the Hydrology, Nitrogen Dynamics, and Plant Growth of a Drained Corn Field in Indiana. Journal of Irrigation and Drainage Engineering 140(8). https://doi.org/10.1061/(Asce)Ir.1943-4774.0000738

Ohio Department of Natural Resources (2006) Rainwater and Land Development: Ohio's Standards for Stormwater Management Land Development and Urban Stream Protection. Ohio Department of Natural Resources, D.o.S.a.W.C. (ed), Columbus, OH.

Papanicolaou, A.N., Elhakeem, M., Wilson, C.G., Burras, C.L., West, L.T., Lin, H., Clark, B. and Oneal, B.E. (2015) Spatial Variability of Saturated Hydraulic Conductivity at the Hillslope Scale: Understanding the Role of Land Management and Erosional Effect. Geoderma 243, 58-68. https://doi.org/10.1016/j.geoderma.2014.12.010

Rawls, W.J., Gimenez, D. and Grossman, R. (1998) Use of Soil Texture, Bulk Density, and Slope of the Water Retention Curve to Predict Saturated Hydraulic Conductivity. Transactions of the Asae 41(4), 983-988. <Go to ISI>://WOS:000075662800010

Rossman, L.A. and Huber, W.C. (2016) Storm Water Management Model Reference Manual: Volume I – Hydrology (Revised). Division, O.o.R.a.D.W.S.a.W.R. (ed), National Risk Management Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH.

Saraswat, D., Frankenberg, J.R., Pai, N., Ale, S., Daggupati, P., Douglas-Mankin, K.R. and Youssef, M.A. (2015) Hydrologic and Water Quality Models: Documentation and Reporting Procedures for Calibration, Validation, and Use. Transactions of the ASABE 58(6), 1787-1797. <Go to ISI>://WOS:000368341900025

Sivapalan, M. and Young, P.C. (2006) Downward Approach to Hydrological Model Development. Encyclopedia of hydrological sciences.

Skaggs, R.W. (1991) Modeling Plant and Soil Systems. Hanks, J. and Ritchie, J. (eds), pp. 205-243, ASA, Madison, WI.

Skaggs, R.W., Youssef, M.A. and Chescheir, G.M. (2012) Drainmod: Model Use, Calibration, and Validation. Transactions of the ASABE 55(4), 1509-1522. <Go to ISI>://WOS:000309089900030

Thornthwaite, C.W. (1948) An Approach toward a Rational Classification of Climate. Geographical Rev. 38(1), 55-94.

Tian, F., Sun, Y., Hu, H. and Li, H. (2016) Searching for an Optimized Single-Objective Function Matching Multiple Objectives with Automatic Calibration of Hydrological Models. Hydrology and Earth System Sciences Discussions, 1-33. https://doi.org/10.5194/hess-2016-88 van Schilfgaarde, J. (1974) Drainage for Agriculture. van Schilfgaarde, J. (ed), pp. 245-270, American Society of Agronomy, Madison, WI.

Warrick, A.W. and Nielsen, D.R. (1980) Applications of Soil Physics. Hill, D. (ed), pp. 319–344, Academic Press, Inc., New York.

Winston, R.J. (2015) Resilience of Green Infrastructure under Extreme Conditions. Doctoral dissertation.

Winston, R.J., Dorsey, J.D. and Hunt, W.F. (2016) Quantifying Volume Reduction and Peak Flow Mitigation for Three Bioretention Cells in Clay Soils in Northeast Ohio. Sci Total Environ 553, 83-95. https://doi.org/10.1016/j.scitotenv.2016.02.081

Youssef, M.A., Abdelbaki, A.M., Negm, L.M., Skaggs, R.W., Thorp, K.R. and Jaynes, D.B. (2018) DRAINMOD-Simulated Performance of Controlled Drainage across the Us Midwest. Agricultural Water Management 197, 54-66.

Youssef, M.A., Skaggs, R.W., Chescheir, G.M. and Gilliam, J.W. (2005) The Nitrogen Simulation Model, DRAINMOD-N Ii. Transactions of the Asae 48(2), 611-626. <Go to ISI>://WOS:000229031800018

CHAPTER III

COMPARISON OF DRAINMOD-URBAN TO THE SWMM LID MODULE FOR BIORETENTION MODELING

3.1 Abstract

Over the last decade, many Low Impact Development (LID) practices have been developed aimed at reducing the negative effects of traditional development on urban hydrology. Bioretention systems have become a leading infiltration-based LID practice to reduce urban stormwater runoff volumes and peak flows. Although these systems have performed well in many site-scale field studies, modeling of bioretention systems has received less attention. Many studies have evaluated hypothetical scenarios of LID installations throughout a watershed and focused on the reduction in runoff volume as a performance metric. Bioretention modeling could be improved by additional studies which calibrate models to field measurements and investigate the performance of individual LID practices such as bioretention instead of lumped LID benefits. DRAINMOD has been applied to bioretention due to its advanced soil-water accounting using the soil-water characteristic curve and its ability to explicitly model underdrains and internal water storage (IWS) zones. This model was recently updated to create DRAINMOD-Urban which is capable of simulations at as small as 1-minute time steps to better match the temporal scale of dynamic, urban stormwater flows. Additionally, the US EPA Stormwater Management Model (SWMM) has become one of the most widely used models for bioretention, and urban drainage systems in general, especially since the release of SWMM5 which included dedicated LID modules. In this study, DRAINMOD-Urban and the SWMM LID module were compared through detailed analysis of the internal processes of each model as well as through model calibration and output investigation. Both SWMM and DRAINMOD-Urban

were evaluated in uncalibrated and calibrated scenarios since urban drainage models often remain uncalibrated for planning scenario analysis. DRAINMOD-Urban was recommended for drainage hydrographs (NSE=0.60) while SWMM produced better overflow hydrographs (NSE=0.58). Drainage produced by SWMM often reached a maximum drainage rate that caused rectangular hydrographs, but DRAINMOD-Urban was better able to match the shape of measured drainage hydrographs. While DRAINMOD-Urban produced good performance of drainage and overflow event volumes when calibrated (drainage NSE=0.83, overflow NSE=0.57-0.66), SWMM tended to be closer to measured volumes even when uncalibrated (drainage NSE=0.77-0.94, overflow NSE=0.67-0.81). This study improved existing knowledge of the SWMM LID module by calibrating to a single bioretention cell. Furthermore, this study addressed hydrographs produced by each model which are important to better understand the effect bioretention has on the flow dynamics of urban watersheds.

3.2 Introduction

Bioretention systems have been widely accepted within the stormwater engineering community due to numerous, geographically diverse field studies demonstrating substantial volumetric reductions and generally good pollutant removal (Olszewski and Davis, 2013; Brown and Hunt, 2012; Davis et al., 2012; Brown and Hunt, 2011a; Davis, 2008; Hunt et al., 2006). However, most bioretention studies have centered on field monitoring studies and laboratory assessments (Liu et al., 2014a; Davis et al., 2009). Computational models have been slow to develop for bioretention systems despite the importance of being able to test bioretention designs prior to implementation. Yet, bioretention modeling allows designers to better predict bioretention cell performance, enhance future bioretention cell designs by providing guidance for design standards, and scale local impacts to the larger watershed.

There are many hydrologic models that have developed tools and/or sub-models for bioretention (see Ch. 1). Many Low Impact Development (LID) models include bioretention as one of many LID practices and examine lumped performance of LID installations compared to traditional development under uncalibrated and calibrated scenarios (Kaykhosravi et al., 2018; Li et al., 2017; Elliott and Trowsdale, 2007). Often these models focus on runoff volume reduction to describe the performance of the bioretention cells. However, hydrologic pathways within a bioretention cell (drainage, overflow, exfiltration and evapotranspiration) should be evaluated since they play a role in water quality treatment and impact watershed hydrology. These studies may be calibrated to field-measured drainage and overflow from a bioretention cell, but too often, that is not the case.

Many current bioretention models have limitations such as the inability to simulate underdrains and internal water storage (IWS) zones despite widespread use in field applications (Ch. 1; Lynn et al., 2018; Liu et al., 2014; Brown, 2011). Further, many models use infiltration processes that assume uniform saturation of the media, while bioretention systems are variably saturated and unsaturated during and following rain events (Barbu and Ballestero, 2015; Akan, 2013; Brown et al., 2013b). Lastly, most models do not adequately account for plant growth and seasonal variation (Ch. 1).

One model in particular, the US EPA Stormwater Management Model (SWMM), is one of the most widely used models for bioretention, especially since the release of SWMM5 which includes dedicated LID modules (Rossman, 2010). SWMM has many applications for catchment hydrology, provides several methods for hydrological and hydraulic processes and other input parameters, and reports hydrographs and peak outflow rate. SWMM has been widely applied to watershed studies investigating lumped LID benefits compared to traditional stormwater management (Avellaneda et al., 2017; Sun et al., 2014; McCutcheon and Wride, 2013; Bosley, 2008). There have been less studies that have calibrated SWMM with bioretention based on an overall runoff reduction (Avellaneda et al., 2017; Li and Lam, 2015; Rosa et al., 2015). These studies are valuable to understand the cumulative effect of various LID installations throughout a watershed.

Bioretention models must first be evaluated at the site scale to ensure that they provide reliable estimations of performance at the watershed scale. Therefore, evaluation of the SWMM LID module performance for site-scale bioretention studies is justified to ensure that any errors in simulated volumes or hydrographs are not propagated throughout the watershed. Some studies have focused on performance of a single bioretention cell (or rain garden) in SWMM compared to column or pilot-scale studies (Gulbaz and Kazezyilmaz-Alhan, 2017; Liu and Fassman-Beck, 2017; Li and Lam, 2015; McCutcheon and Wride, 2013). These studies provide insight on how bioretention systems are represented in SWMM and how hydrograph outputs from SWMM compared to measured hydrographs. Further studies have compared SWMM with other bioretention models such as HYDRUS-1D (Lynn et al., 2018), WinSLAMM (Tiveron et al., 2018), HM-RWB (Gulbaz and Kazezyilmaz-Alhan, 2017), RECARGA (Sun et al., 2011) and HydroCAD (Lucas, 2010). These studies have proved that SWMM is capable of modeling bioretention cells under a variety of conditions, but it does have limitations. This study combined important aspects of each of these studies: site-scale evaluation of the SWMM LID module, calibration of hydrologic pathways in the SWMM LID module using field measured data instead of simply estimating runoff reduction, and comparison of SWMM to another promising bioretention model, DRAINMOD-Urban.

DRAINMOD is an agricultural drainage model that has performed well when applied to bioretention systems by addressing some of the limitations of other models (Winston, 2015; Hathaway et al., 2014; Brown et al., 2013b). DRAINMOD-Urban is a version of DRAINMOD adapted for urban hydrologic response times. DRAINMOD-Urban showed good prediction (NSE=0.60) of observed drainage hydrographs from a bioretention cell (Lisenbee et al., 2020). DRAINMOD-Urban was considered for this study because it has a detailed soil-water accounting procedure that estimates water level fluctuations in the cell using the soil water characteristic curve (SWCC). The SWCC is a better representation of the available pore space in the bioretention cell at various depths compared to the common assumption that storage capacity is simply the saturated water content minus the water content at field capacity (Brown et al., 2013b). This is especially important in bioretention systems that are variably saturated, especially those employing IWS zones which elevates the internal water level. In addition to the sophisticated soil-moisture accounting, the SWCC is used in DRAINMOD-Urban for determining the volume drained and the Green-Ampt infiltration parameters at various internal water levels within the bioretention cell. DRAINMOD-Urban produces hydrographs at time steps down to one minute for each of the hydrologic pathways in the bioretention cell (inflow, overflow, infiltration, drainage, exfiltration and ET). This study expanded on the previous calibration study of DRAINMOD-Urban (Lisenbee et al., 2020) by comparing the drainage and overflow hydrographs and model performance to that of the SWMM LID module.

While DRAINMOD-Urban appears to be well-suited for modeling bioretention, it also has some disadvantages compared to SWMM. SWMM has an easy to use graphical user interface (GUI) and graphing functions for instant visualization of outputs. Conversely, DRAINMOD-Urban outputs text files that must undergo rigorous post-processing with an external program. Furthermore, SWMM is a watershed-scale model that can capture dynamics between catchments, hydraulic structures and other bioretention cells upstream and downstream of any given bioretention cell. It also incorporates routing procedures to account for travel time and friction losses between these objects. DRAINMOD-Urban can only model a single bioretention cell. While site-scale modeling is beneficial to evaluate effects of various design parameters or performance of a specific bioretention cell, watershed-scale modeling is useful for planning purposes and broader ecosystem-level investigation. However, watershed-scale models for bioretention tend to lump parameters and make simplifications to allow for quick analysis of many contributing factors without cumbersome input requirements. To combine the best of these methods, site-scale models can be incorporated as add-in tools for larger watershed models.

This study addressed the need to understand the performance of bioretention modeling in a common hydrologic model, SWMM, and to calibrate SWMM to field-measured bioretention cell outputs. To meet this objective, 2-minute drainage and overflow hydrographs from a monitored bioretention cell was used to calibrate SWMM. The resulting model performance was compared with that of DRAINMOD-Urban. Evaluating hydrographs produced by each model was important to consider the effect bioretention has on the flow dynamics of urban watersheds. This study identified strengths and weaknesses of each model's ability to represent the event volumes and hydrographs of drainage and overflow pathways in a bioretention cell. Acknowledging the advantages of each model and the applications best suited to each bears potential for combining these strengths in future bioretention modeling efforts.

3.3 Materials and Methods

3.3.1 Site Description

The Ursuline Cell (UC) located near Cleveland, Ohio, USA, was used for previous evaluations of DRAINMOD and DRAINMOD-Urban performance and sensitivity allowing a comparison to analogous modeling performed in SWMM (Lisenbee et al., 2020; Winston, 2015). A 3600 m^2 drainage area comprised largely of parking lot (77% impervious) produced stormwater runoff that entered the UC cell. The bioretention media used in the UC cell was 87% sand, 4% silt, and 9% clay according to sieve analysis (ASTM, 2007). Each layer of the UC cell is described in more detail in Chapter 2, but a diagram can be found in Figure 3.2.

The precipitation was measured on-site with a tipping bucket rain gauge at 1-minute intervals. The inflow for UC was unable to be directly measured on-site so catchment properties were entered into SWMM to create a runoff hydrograph from the drainage area that was used as inflow to the bioretention cell in both models. The combined drainage and overflow were measured with a 60-degree, sharp-crested, v-notch weir, and a Hobo U20 pressure transducer that collected data every two minutes. These two flows were separated in SWMM using a rating curve based on the internal water level (Winston et al., 2016). A total of 12 drainage events and four overflow events were measured over the seven-month monitoring period. The monitoring of the UC site is described further in Lisenbee et al. (2020) and Winston et al. (2016).

3.3.2 Governing Equations

For direct comparison to DRAINMOD-Urban, the bioretention LID module in SWMM was evaluated in this study as its own subwatershed. This reduced SWMM to a single bioretention cell model like DRAINMOD-Urban and provided valuable analysis of the capabilities of LID module for bioretention cell modeling. Before modeling these bioretention cells in SWMM, the governing equations used for various hydrologic pathways in SWMM and DRAINMOD-Urban were compared. More information on model processes can be found in model documentation (Rossman and Huber, 2016a; "DRAINMOD 6.1 Help File," 2013; Skaggs et al., 2012).

Both DRAINMOD-Urban and SWMM are long-term, continuous simulation models which account for antecedent moisture conditions. SWMM also has the benefit of routing procedures such as the kinematic wave equation which accounts for the runoff travel time to the bioretention cell. The routing procedures in SWMM also allow for outflow to be routed to another LID component or pipe network downstream.

3.3.2.1 Inflow

For the UC cell, inflow was unable to be measured on site, so SWMM was used to calculate a 1-min runoff hydrograph from the drainage area using a nonlinear reservoir model that incorporated Manning's equation for overland flow and accounted for depression storage. The Green-Ampt infiltration method was also enabled for the pervious portion of the drainage area (although it was 77% impervious). For DRAINMOD-Urban, this runoff was entered as the inflow to the bioretention cell. In the SWMM simulations, the same method was used to calculate runoff from the drainage area except for a PET file using the Penman-Monteith method which slightly reduced the inflow to the bioretention cell.

3.3.2.2 Overflow

DRAINMOD-Urban has a set surface storage that represents the ponding zone. If the ponding exceeds this level, then overflow is equal to the sum of direct precipitation on the bioretention cell and inflow minus the infiltration. SWMM includes a ponding zone (denoted berm height) in the LID module for bioretention but also includes a vegetation volume fraction to account for the space that vegetation occupies in the ponding zone. In the surface water balance of the LID module, overflow is modeled as the sum of precipitation and inflow minus the sum of infiltration and evapotranspiration at the surface (Eqn. 1),

$$\phi_1 \frac{\partial d_1}{\partial t} = i + q_0 - e_1 - f_1 - q_1 \qquad \text{(Eqn. 1)}$$

where ϕ_1 is the void fraction of surface volume (freeboard above surface minus volume of vegetation), d_1 is the depth of water on the surface (ft), i is the precipitation rate falling directly on the bioretention cell surface (ft/s), q_0 is the inflow from the drainage area (ft/s), e_1 is the surface ET rate (ft/s), f_1 is the infiltration rate at the surface (ft/s), and q_1 is the overflow rate (ft/s) (Rossman and Huber, 2016a). Overflow is calculated in the model as the water level above a maximum freeboard for each given timestep (Eqn. 2),

$$q_1 = \max\left[\frac{d_1 - D_1}{\Delta t}, 0\right] \qquad \text{(Eqn. 2)}$$

where D_1 is the freeboard height for surface ponding (ft) (Rossman and Huber, 2016a).

3.3.2.3 Evapotranspiration

Both DRAINMOD-Urban and SWMM accept user-input potential evapotranspiration (PET) but DRAINMOD-Urban can also calculate PET using the Thornthwaite method. With the Thornthwaite method, PET is distributed uniformly across the 12 hours between 6:00 AM and 6:00 PM. Hourly PET is set to zero whenever rainfall occurs within that hour. In DRAINMOD-Urban, the PET is used to represent the ET from the system when the soil water is not limiting. If the ET is limited by the soil water conditions such as when the soil moisture in the root zone is below the permanent wilting point, then ET is equal to the upward flux of water as a function of the water table depth (which is determined from the SWCC soil input). When this upward flux is not enough to meet the ET demand, water is removed from the root zone.

In SWMM, the ET is calculated for the surface, soil layer, and storage layer consecutively such that any remaining PET is available to the subsequent layer. The surface ET is calculated as the minimum of the PET and the ponding depth at a given timestep (Eqn. 3). The ET from the soil layer is the minimum of the PET minus the surface ET and the moisture content above wilting point times the depth of the soil layer (Eqn. 4). The ET can also be calculated for the storage layer when the soil layer is unsaturated. This is represented as the minimum of the PET minus the soil ET and surface ET and the void fraction of the storage layer times the depth of water in the storage layer (Eqn. 5). The storage ET is set to zero when the soil layer is saturated, and both the soil and storage ET are set to zero when surface infiltration is occurring.

$$e_1 = \min\,[PET, d_1/\Delta t] \qquad \text{(Eqn. 3)}$$

$$e_2 = \min\,[PET - e_1, (\theta_2 - \theta_{WP})D_2/\Delta t] \qquad \text{(Eqn. 4)}$$

$$e_3 = \min\,[PET - e_1 - e_2, \phi_3 d_3/\Delta t] \qquad \text{(Eqn. 5)}$$

Where e_1 is the surface ET, e_2 is the soil layer ET, and e_3 is the storage layer ET and θ_2 is the moisture content in the soil layer, θ_{WP} is the moisture content at wilting point, D_2 is the depth of the soil layer, ϕ_3 is the void fraction of the storage layer, and d_3 is the depth of water in the storage layer.

3.3.2.4 Infiltration

The Green-Ampt method was used to represent surface infiltration through the bioretention cell in both SWMM and DRAINMOD-Urban. This method is a simplification of Richards' equation which employs certain assumptions such as one-dimensional, vertical flow and total saturation behind a sharp wetting front. These assumptions are not always valid in bioretention cells which operate under variably saturated and unsaturated conditions. For the LID editor in SWMM, the Green-Ampt equation was adjusted to account for ponding depth which is an important component of bioretention cells.

DRAINMOD-Urban also requires the SWCC of the bioretention media to account for soil moisture changes in bioretention media; this is especially important for cells with an IWS zone when the internal water table is close to the surface. The SWCC gives a more detailed relationship between moisture content fluctuations and depth to the internal water level than the traditional methods of assuming an initial moisture deficit which is used in SWMM (Brown et al., 2013). This was especially true when the water table was close to the surface as it often is in a bioretention cell during a storm event. Therefore, the SWCC is hypothesized to improve infiltration estimation in DRAINMOD-Urban compared to SWMM which does not require sophisticated soil characteristic parameterization. For SWMM, the infiltration capacity recovery is done simply using the hydraulic conductivity used in Green-Ampt instead of using a soil-accounting method like DRAINMOD-Urban (Bosley, 2008). SWMM assumes all soil moisture is evenly distributed throughout the soil layer and soil matric forces are ignored such that the entire system acts as a simple storage reservoir (Rossman and Huber, 2016).

DRAINMOD-Urban and SWMM require different inputs although they use the same Green-Ampt equation. In SWMM, the Green-Ampt input parameters are the soil capillary suction head (cm), saturated hydraulic conductivity (cm/hr), and the initial soil moisture deficit (porosity minus the initial soil moisture). The SWMM reference manual provides a table of suggested bioretention soil parameters based on sand, loamy sand, and sandy loam soil textures using the SPAW model (Rossman and Huber, 2016a; Saxton and Rawls, 2006). In DRAINMOD, the Green-Ampt equation is written in terms of two coefficients, A and B:

$$f = \frac{A}{F} + B \qquad \text{(Eqn. 6)}$$

where f is the Green-Ampt infiltration rate (cm/hr), F is the cumulative infiltration (cm), and A and B are constants such that,

$$A = K_s M S_{av} \qquad \text{(Eqn. 7)}$$

$$B = K_s \tag{Eqn. 8}$$

where K_s is the vertical saturated hydraulic conductivity (cm/hr), M is the fillable porosity or the saturated moisture content minus the moisture content at the given water table depth (cm^3/cm^3), and S_{av} is the suction at the wetting front (cm). These coefficients are derived automatically from the SWCC entered in the model, but they can be adjusted manually if desired (Skaggs et al., 2012). Deriving these infiltration parameters from a measured SWCC can provide a more accurate estimation of these parameters than the suggested empirical estimations based on soil texture in SWMM.

3.3.2.5 Percolation

DRAINMOD-Urban also uses the Green-Ampt equation between soil layers within the bioretention cell. The Green-Ampt parameters derived from the SWCC and K_{sat} for each soil layer in the model are used to find an effective K_{sat} based on the internal water table depth. Although Green-Ampt is used to estimate the infiltration at the surface, SWMM uses Darcy's law to simulate percolation through subsequent soil layers in the bioretention cell. This is applied in the same manner as SWMM's groundwater routine using the coefficient, HCO, to describe the exponential decrease in hydraulic conductivity with decreasing moisture content (Rossman and Huber, 2016a). The equation used for the percolation rate through each soil layers is:

$$f_2 = K_{sat} e^{(-HCO(\phi - \theta))} \tag{Eqn. 9}$$

where K_{sat} is the saturated hydraulic conductivity of the soil layer, HCO is the conductivity slope, ϕ is the soil porosity and θ is the soil moisture in the soil layer. If the native soil layer is saturated, the infiltration is limited by the saturated hydraulic conductivity of the soil layer. If the moisture content of the soil layer falls below field capacity, then the percolation rate goes to zero. A flux limit is added to the percolation rate such that the minimum is applied when the available drainable water and the net amount of water added to the soil layer from infiltration and ET at each time step is less than the percolation rate calculated using Darcy's equation (Rossman and Huber, 2016a).

3.3.2.6 Drainage

DRAINMOD-Urban has the capability of representing underdrains in bioretention systems (Figure 3.1) by using the Hooghoudt drainage equation that accounts for flow convergence near the drains:

$$q = 4K_e m(2d_e + m)/L^2 \qquad \text{(Eqn. 10)}$$

where q is the drainage rate (cm/h), m is the midpoint water level above the drain, K_e is the equivalent lateral hydraulic conductivity of the profile (cm/h), d_e is the equivalent depth from the drain to the restrictive layer (cm), and L is the drain spacing (cm).

DRAINMOD-Urban's soil-moisture accounting is also used to estimate the change in the internal water level. When the water level begins to pond at the soil surface and the cell is fully saturated, the Kirkham equation (1957) is used to calculate drainage. These two equations are used to calculate the rate of water movement through the soil to the drain(s) at given water table elevations (Skaggs et al., 2012). However, the drainage rate could be limited by other hydraulic constraints which are accounted for through the drainage coefficient parameter which sets the maximum drainage capacity. DRAINMOD-Urban also provides a "controlled drainage" option that uses weir settings to control the drawdown in the bioretention cell and represent an IWS zone, a common design in practice.

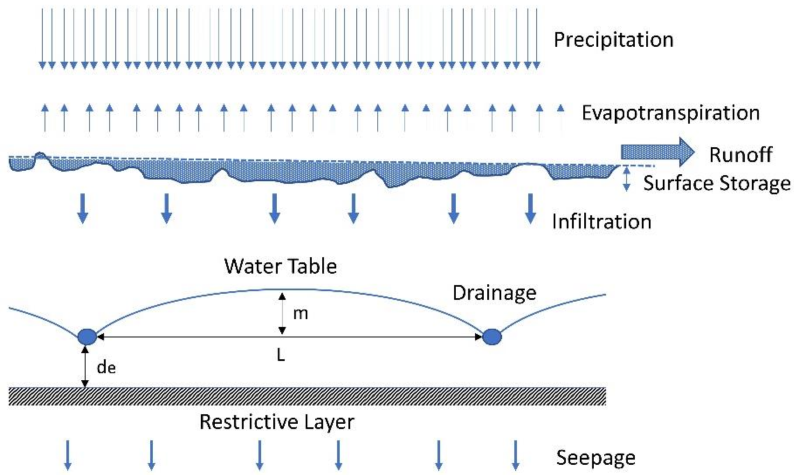


Figure 3.1. Schematic of DRAINMOD water balance including variables for the Hooghoudt drainage equation.

SWMM can model underdrains in the LID module but the drainage inputs required are not measurable quantities, and the drain advisor that assists users in determining the correct values for these inputs is limited in scope ("EPA SWMM Help File 5.1," 2017). According to the SWMM LID user manual, SWMM models the underdrain using an empirical power law weir equation unless the maximum drainage is reached:

$$q = C_D(h)^{\eta} \tag{6}$$

Where q is the drainage rate (ft/s), h is the hydraulic head (ft), C_D is the underdrain discharge coefficient, and η is the underdrain discharge exponent (Rossman and Huber, 2016a). The offset height set in the LID module defines the hydraulic head on the underdrain. There is no flow through the underdrain until the water level in the storage layer reaches the drain offset height. The maximum drainage limit is equal to the drainage coefficient (as represented in DRAINMOD-Urban) if the exponent is set to zero. Under this scenario, SWMM suggests calculating the drainage coefficient to be equal to the flow rate when the underdrain pipe is flowing full (using Manning's equation) divided by the bioretention area (Rossman and Huber, 2016a). However, if the underdrain is not limiting the system, the drainage coefficient can be any number larger than the K_{sat}. In this case, the drainage rate is equal to the rate of percolation entering the underdrain from the adjoining soil layer minus the seepage rate as long as the maximum drainage limit (represented by the drainage coefficient) is not reached. Other drainage restrictions can be incorporated by adjusting the drainage exponent to 0.5 to represent the standard orifice equation (Rossman and Huber, 2016a). Under this scenario, the drainage coefficient can be used to represent slotted pipes (that act as orifices) or an orifice at the outlet of the underdrain. These adjustments to equation 6 offer more flexibility in how the drainage hydraulics are calculated by considering multiple drains, valves, cap orifices, slotted pipes, etc. which are not considered in many bioretention models. However, an upturned elbow (for creation of an IWS zone) is one drainage configuration that is still not available in the SWMM LID module.

Few modeling studies have investigated bioretention cells with IWS zones. One study has shown how to represent an elevated outlet in SWMM by creating a rating curve using the external model HYDRUS to represent both unsaturated zones and saturated sections such as the IWS zone (Lynn et al., 2018). However, this study was conducting using the original SWMM framework. No studies to date have modeled an IWS zone with the current LID module.

In this study, for comparison to DRAINMOD-Urban, the cell configuration had to be adjusted in SWMM to account for the storage available in the IWS zone. The underdrain in SWMM was placed at the top of the IWS zone (60 cm from bottom of cell) and the other layers were offset to accommodate this underdrain placement. The storage layer depth was expanded beyond simply the depths of the gravel and sand layers (45 cm) to include the entire IWS zone (60 cm), and the depth of the bioretention media was reduced (from 60 cm as measured to 45 cm) to exclude the amount of media considered part of the IWS storage layer (Figure 3.2). In SWMM, the soil layer or bioretention media can only be placed above the storage layer and the underdrain is typically placed at the top of the storage layer. Therefore, to accommodate the proper underdrain invert elevation, the storage layer included the IWS. When the IWS zone was full and the bioretention cell was draining, this drainage design should represent the function of the IWS zone. However, the drawback was that the storage layer has a larger K_{sat} which could affect the function when the IWS zone was unsaturated.

3.3.2.7 Exfiltration

In SWMM, the exfiltration from the bottom of the storage layer into the surrounding native soil below the bioretention cell is simply set to a user-supplied saturated hydraulic conductivity of the native soil.

At the transition from the storage layer to the underlying soil, DRAINMOD-Urban uses Darcy’s law with the Dupuit-Forchheimer assumptions to calculate vertical seepage. The model also requires seepage parameters inputs such as the piezometric head of the

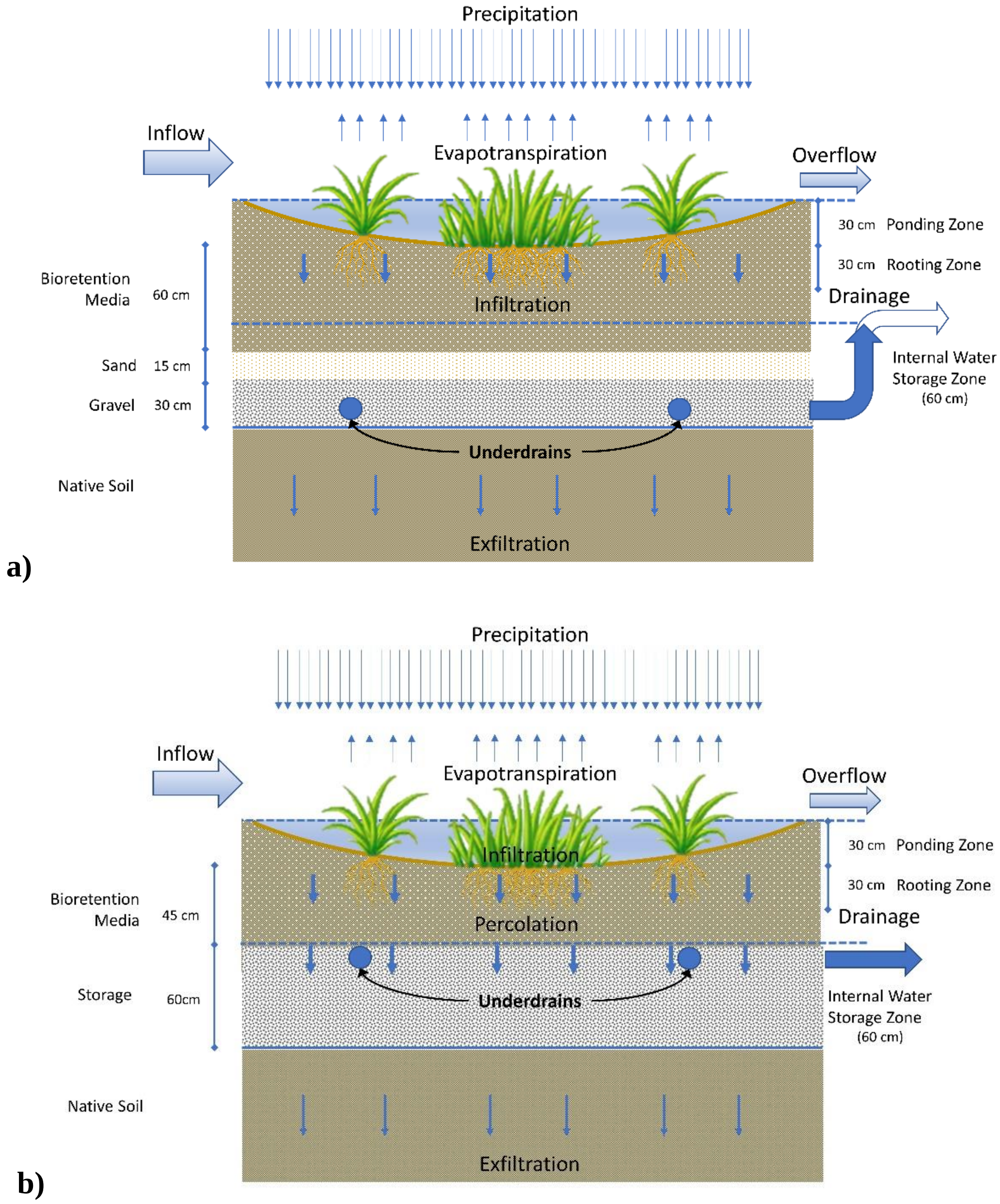


Figure 3.2. Comparison of the drainage configuration used in DRAINMOD-Urban (a) and SWMM (b) to represent the internal water storage zone (IWS) present in the Ursuline College (UC) bioretention cell.

aquifer, the thickness of the restricting layer and the vertical conductivity of the restricting layer which are often used as calibration parameters since they are difficult to measure.

3.3.3 Modeling Methods

3.3.3.1 Inputs

It is important to describe the differences in inputs required by each model to understand if the model utilizes inputs that characterize the mechanisms of the bioretention cell. The complexity and number of inputs required can discourage the use of a model especially with designers that are less familiar with hydrologic modeling. The right balance must be struck between accurately representing the system and reducing the effort required to measure or estimate inputs.

SWMM requires fewer inputs than DRAINMOD-Urban but more inputs are simply estimated with guidance from the model or left as defaults (Rossman and Huber, 2016a). A total of 15 inputs are required specifically for the LID module and six of those are soil parameters. DRAINMOD-Urban has fewer estimated parameters but requires more detailed collection of soil characteristics such as the SWCC and hydraulic conductivity of each layer which require extensive laboratory testing (Table 3.1).

Table 3.1. Comparison of initial uncalibrated inputs required for both SWMM and DRAINMOD-Urban (DM-Urban) for the Ursuline College (UC) bioretention cell (BRC). Calibration parameters are denoted and the change in these parameters can be found in Table 3.2.

			DRAINMOD-Urban	SWMM	Measured (M) or Estimated (E)	Calibration Parameters
Catchment Properties	Geometry	Catchment Area (m^2)	-	3600	M	
		Catchment Width (m)	-	43.6	M	
		% Slope	-	4.49	M	
	Land Cover	% Imperviousness	-	77	M	
		Impervious Manning's n	-	0.01	E	
		Pervious Manning's n	-	0.1	E	
		Depression Storage (cm)	-	0.127	E	
		% of Impervious Area w/o Depression Storage	-	25	E	
	Runoff	User-defined Inflow	From SWMM	n/a		
BRC Design Properties	Geometry	BRC Area (m^2)	-	182	M	
		BRC Area**:** Catchment Area Ratio	19.7	-	M	
		BRC Width (m)	-	7.01	M	
	Ponding Layer	Ponding Layer Depth (cm)	30	30	M	
		Surface Slope	-	0	E	
	Drainage	Underdrain Diameter (cm)	10	-	M	
		Underdrain Flow (Drainage) Coefficient (cm/day)	300	300	E	**DM-Urban**
		Underdrain Flow Exponent	-	0	E	
		Underdrain Offset Height (cm)	-	60	E	
		Depth from Soil Surface to Drain (cm)	107	-	M	
		Drain Spacing (cm)	597	-	E	
		Weir Depth from Soil Surface (for IWS zone)	52	-	M	
	BRC Media	BRC Media Depth (cm)	60	45	M	
		BRC Surface Roughness (Manning's)	-	0.1	E	
		Initial Water Table Depth (cm)	112.5	-	E	
	Storage Layer	Storage Layer Depth (cm)	45	60	M	
		Storage Void Ratio	-	0.514	E	**SWMM**
		Clogging Factor	-	0	E	
		Piezometric Head (cm)	53	-	E	**DM-Urban**
		Thickness of Restricting Layer (cm)	55	-	E	**DM-Urban**
		Seepage Rate (cm/hr)	0.437	0.437	M	**SWMM**

Table 3.1 (continued). Comparison of initial uncalibrated inputs required for both SWMM and DRAINMOD-Urban (DM-Urban) for the Ursuline College (UC) bioretention cell (BRC). Calibration parameters are denoted and the change in these parameters can be found in Table 3.2.

			DRAINMOD-Urban	SWMM	Measured (M) or Estimated (E)	Calibration Parameters
Climate		Precipitation	1-min measured data		M	
		Temperature	Daily min/max	-	M	
		Heat Index	50	-	E	
		User-input PET	n/a	Penman-Montieth	E	
Soil	**BRC Media**	Soil Texture	Loamy Sand		M	
		Porosity	0.331	0.331	M	
		Initial Moisture Deficit		0.154	E	
		Field Capacity Moisture Content	0.177	0.177	M	
		Wilting Point Moisture Content	0.02	0.047	E	
		Suction Head (cm)	-	6.10	E	**SWMM**
		Saturated Hydraulic Conductivity (cm/hr)	16	16.8	M	**DM-Urban/ SWMM**
		Soil-Water Characteristic Curve	required	-	M	
	Other	Saturated Hydraulic Conductivity of Mulch	60	-	E	
		Saturated Hydraulic Conductivity of Sand	15	-	E	**DM-Urban**
		Saturated Hydraulic Conductivity of Gravel	200	-	E	
		Hydraulic Conductivity Slope (HCO)	-	49.4	E	**SWMM**
Vegetation		Root Layer Depth (cm)	30	-	E	
		Vegetation Volume Fraction	-	0.01	E	
Summary		**Total Required Inputs (minus inflow)**	26	24		
		Total Estimated	11	13		
		Total Measured	15	11		
		Total Calibration Parameters	5	5		

3.3.3.2 Calibration Parameters

Calibration parameters are important to understand how models are adjusted to find the best fit to measured data. Calibration parameters tend to be those that cannot be measured, are difficult to measure, or that have more inherent uncertainty in their measured values such as the saturated hydraulic conductivity (K_{sat}). The calibration parameters used in DRAINMOD-Urban were the saturated hydraulic conductivity of the bioretention media, the saturated hydraulic conductivity of the sand layer, the drainage coefficient, the piezometric head and the thickness of the restricting layer (Table 3.2). Previous studies have identified saturated hydraulic conductivity (K_{sat}), soil moisture at field capacity, and initial moisture deficit as sensitive parameters in SWMM when calibrating bioretention models (Dietrich et al., 2017; Liu and Fassman-Beck, 2017; Rosa et al., 2015). K_{sat} was expected to have significant impact on the drainage and overflow because of its effect on the infiltration in the Green-Ampt equation and in the percolation equation. Although K_{sat} had an impact on maximum drainage rate and the model calibration was sensitive to this parameter, the calibration that produced the best drainage and overflow hydrographs used the measured K_{sat}. The drainage coefficient in DRAINMOD-Urban was increased to a large value to avoid placing restrictions on drainage flow rate since measured hydrographs did not show any evidence of drainage restriction. For comparison the same was done in SWMM. An elevated drainage coefficient was also used in a study by Brown (2011) who assumed drainage was more likely to be limited by hydraulic conductivity of the soil or drain depth and spacing.

The calibration parameters used in SWMM were the suction of the bioretention media, the conductivity slope (HCO), and the void ratio of the storage layer (Table 3.2). The seepage rate was also adjusted to achieve better drainage volumes but only for the volume calibration (see next section). The conductivity slope (HCO) was used in the SWMM equation for percolation through the soil layers (Eqn. 9). The SWMM help file provides guidance on this parameter suggesting that it should fall in the range of 30 to 60 and can be estimated from soil texture given an equation provided ("EPA SWMM Help File 5.1," 2017). Several studies have shown much smaller HCO values than suggested by SWMM in bioretention simulations (Lynn et al., 2018; Liu and Fassman-Beck, 2017; Rosa et al., 2015). Therefore, although the HCO was roughly calculated to be 49.4 based on SWMM recommendations, several smaller HCO values were included in the calibration of the UC cell ranging from 7 to 60.

3.3.3.3 Calibration Process

When calibrating both models to match measured drainage and overflow hydrographs, it was important to evaluate the effect of calibration on event and total volumes as well. Sometimes these processes work together: calibrating hydrographs also improves event volumes. However, an attempt to match volumes can sometimes distort the shape of the hydrograph (Lisenbee et al., 2020). Therefore, both hydrographs and volumes were evaluated under uncalibrated, volume-calibrated, and hydrograph-calibrated simulations in DRAINMOD-Urban and SWMM.

For DRAINMOD-Urban, the calibration process was described in detail in Lisenbee et al. (2020). The primary goodness of fit tests, NSE and PBIAS, were used to determine the calibration that produced simulated drainage and overflow hydrographs that best matched measured hydrographs. Drainage and overflow hydrographs were also analyzed by visual

Table 3.2. Calibration parameters for the Ursuline College (UC) bioretention cell in DRAINMOD-Urban and SWMM

	PIEZO. HEAD* (cm)	RESTRICT. LAYER* (cm)	KSAT-sand (cm/hr)	KSAT-media (cm/hr)	DRAIN COEFF.	HCO	VOID*	SOIL SUCTION (cm)	SEEPAGE (cm/hr)
DM-Urban									
Uncalibrated	53	55	15	16	25				
Volume-Calibrated	23	26.5	30	17	120				
Hydrograph-Calibrated	12	20	45	35	300				
SWMM									
Uncalibrated				16.8	300	49.4	0.51	6.10	0.44
Volume-Calibrated				13.3	300	23.0	0.30	25.4	1.3
Hydrograph-Calibrated				16.8	300	23.0	0.30	11.0	0.44

*PIEZO. Head=Piezometric head, RESTRICT LAYER=thickness of the restricting layer, VOID=void ratio of the storage layer inspection and by comparison of peak flow, time to peak and duration. Following this hydrograph calibration, the NSE and percent error were calculated to compare measured and modeled drainage and overflow event volumes.

Additionally, DRAINMOD-Urban was calibrated to the event volumes based on the calibration suggested by Winston (2015) in the original DRAINMOD model (Lisenbee et al., 2020). The NSE and PBIAS for drainage and overflow event volumes and hydrographs were calculated under this calibration scenario. For comparison, NSE and PBIAS for drainage and overflow event volumes and hydrographs were calculated for an uncalibrated DRAINMOD-Urban model using measured and estimated inputs listed in Table 3.1.

For SWMM, an uncalibrated simulation was used as a baseline with measured input parameters and approximations for inputs that were not measured (Table 3.1). The performance of the uncalibrated SWMM simulation was especially relevant because many studies have only used SWMM in an uncalibrated state. Goodness-of-fit tests (NSE and PBIAS) were calculated for this initial simulation and hydrographs were visually examined.

Next, a batch file for SWMM was created using Python 3.8.2 (Python Software Foundation, https://www.python.org/) which explored ranges of various input parameters such as soil properties, drainage coefficient, void ratio in the storage layer, and hydraulic conductivity slope (HCO). In the SWMM calibration, the NSE and PBIAS were used to determine model fit among drainage and overflow hydrographs. Other statistics such as the index of agreement (d), its relative error counterparts (d_1) and the relative NSE (E_1) were calculated as supplementary to the NSE and PBIAS during calibration (Moriasi et al., 2007). The drainage coefficient was set to a large value so that the model behaved as if there were no restrictions on the drain (similar to what was done in DRAINMOD-Urban). The HCO and K_{sat} seemed to have the largest influence on goodness of fit tests. Both of these parameters were optimized first under baseline conditions for all other parameters. However, despite testing a range of K_{sat}, the simulation that had the best performance for drainage and overflow hydrographs used the measured K_{sat}. Therefore, in this case, hydrograph calibration did not require adjusting the K_{sat}. Next, simulations with both calibrated K_{sat} and HCO were carried out for other parameters such as soil, storage and seepage properties.

After the statistics mentioned above were used to narrow the number of viable scenarios, hydrographs were visually inspected, and cumulative and event volumes were summed and compared to observed values. Next, characteristics such as peak flow, time to peak, and event duration were compared for each outflow-producing event. These assessments aided in determining a final hydrograph-calibrated simulation for the UC cell. Following the hydrograph-calibration, SWMM calibration parameters were further adjusted to achieve event-based aggregated drainage and overflow volumes that are closest to the measured volumes. This was referred to as the volume-calibration.

3.4 Results

3.4.1 DRAINMOD-Urban Performance

<u>3.4.1.1 Hydrographs</u>

The UC cell was previously calibrated with DRAINMOD-Urban to high temporal resolution drainage hydrographs (Lisenbee et al., 2020). When calibrating DRAINMOD-Urban to measured hydrographs, good performance was achieved with NSE=0.60 for drainage hydrographs at a 2-minute timestep (Table 3.3). When the UC cell was calibrated to achieve the best fit to measured drainage and overflow volumes (volume-calibration), the hydrograph performance was reduced beyond even the uncalibrated simulation (Table 3.3). According to Skaggs et al. (2012), an NSE>0.4 is acceptable model performance at a daily timestep. For a much smaller 2-minute timestep, both the uncalibrated and volume-calibrated drainage hydrographs could be considered acceptable performance at 0.39 and 0.31 NSE. For overflow hydrographs, however, all calibrations performed poorly. This could be explained by the emphasis of peak flow in the NSE statistic (Broekhuizen et al., 2020; Lisenbee et al., 2020). While modeled timing and duration of overflow were very close to measured, the peak flow was overestimated in all DRAINMOD-Urban simulations (Figure 3.6).

Visualization of drainage and overflow hydrographs give a good indication of DRAINMOD-Urban performance (Figure 3.3 & 3.4). The performance of DRAINMOD-Urban drainage hydrographs varies depending on the calibration method. The volume-calibration had the worst drainage hydrograph fit (Figure 3.3c). This simulation had a truncated peak that was much lower than measured and, to compensate for this loss in volume, the duration of the first two peaks was extended. The uncalibrated simulation created a drainage hydrograph slightly better than the volume-calibrated one because the peak did not plateau (Figure 3.3a). Although the peak and duration of the uncalibrated drainage hydrograph was still poorly represented, the shape of the hydrograph was better than the rectangular shape observed under the volume calibration. In both the uncalibrated and volume-calibrated simulations, the third peak was not detected. The hydrograph-calibrated drainage hydrographs were improved in multiple ways. The peak was closer to measured (although still underestimated), the timing of the rising and falling limbs was much closer to measured, and the third peak was well-represented regarding timing and peak flow (Figure 3.3e). It is obvious that drainage hydrographs benefited from hydrograph-calibration in DRAINMOD-Urban. For overflow hydrographs, the improvements across calibrations are less evident. The peaks are reduced, and the timing is improved under hydrograph calibration particularly for the second smaller peak (Figure 3.4a, c, e).

3.4.1.2 Volume

The event volumes showed higher NSEs than the hydrographs for all calibration sets except for the uncalibrated overflow which showed poor performance for both volumes and hydrographs (Table 3.3). This is expected because the event volumes are summed over the entire event and the hydrographs are evaluated at each 2-minute interval. Small shifts in the modeled hydrograph can lead to changes in the hydrograph NSE although it may have little impact on the modeled volume.

The hydrograph-calibrated DRAINMOD-Urban described in Lisenbee et al. (2020) achieved an NSE=0.83 for drainage event volumes. Overflow achieved good performance for overflow event volumes (NSE=0.66) even though the NSE for overflow hydrographs was poor. The NSE of drainage volumes under the volume-calibration was actually the same at 0.83 as the hydrograph calibration but with slightly better PBIAS. The volume-calibration of overflow had a lower NSE and PBIAS compared to the hydrograph-calibration. Interestingly, the uncalibrated DRAINMOD-Urban still had a poor fit to overflow volumes (Table 3.3). Drainage and overflow volumes were mostly underestimated when DRAINMOD-Urban was uncalibrated except for a few storms with the highest measured volumes (Figure 3.5a). Both calibration techniques (i.e. volume or hydrograph calibrated) yielded decent drainage volumes compared to measured volumes though still slightly underestimated (Figure 3.5c & 3.5e). With only four overflow events for comparison, it is harder to detect a trend in overflow volumes (Figure 3.5). However, both volume and hydrograph calibrations significantly improved drainage and overflow volumes suggesting that for DRAINMOD-Urban calibration is highly recommended.

3.4.2 SWMM Model Performance

3.4.2.1 Hydrographs

The uncalibrated SWMM model simulated overflow hydrographs (NSE=0.52) that matched measured overflow hydrographs almost as well as SWMM when calibrated to the hydrographs (NSE=0.58). Drainage hydrographs showed greater improvement with hydrograph calibration from an NSE=0.25 uncalibrated to NSE=0.42 (Table 3.3). However, when examining drainage event hydrographs, the difference between the uncalibrated (b) and hydrograph-calibrated (f) simulations are less visually obvious, likely improving the NSE due to better timing (Figure 3.3). When K_{sat} and seepage rate were adjusted in SWMM to achieve better drainage and overflow volumes (volume-calibration), the maximum drainage rate underestimated the measured peak flow instead of overestimating peak flow (in other calibration sets). This change was not represented by the cumulative NSE which shows only a change from 0.41 to 0.42 from volume-calibration to hydrograph-calibration. Interestingly, the cumulative NSE for overflow hydrographs dropped sharply when calibrated to volumes compared to the uncalibrated and hydrograph-calibrated simulations, but other goodness-of-fit tests do not demonstrate as drastic a decline in performance (Table

3.3). Again, this is likely due to the NSE being highly influenced by peak matching. The event overflow hydrograph in Figure 3.4 (b, d, f) did not show much change across simulations except for a larger second peak in the volume-calibration which could explain some of the change in NSE.

3.4.2.2 Volume

The NSE for event drainage volumes reduced from 0.93 uncalibrated to 0.77 under the hydrograph calibration due to overestimation (Table 3.3, Figure 3.5a, Figure 3.5e). Similarly, the NSE of overflow event volumes was reduced from an uncalibrated 0.73 to 0.67 under the hydrograph calibration. Naturally, drainage and overflow event volumes had the best performance (NSE=0.94 and NSE=0.81, respectively) when SWMM was calibrated specifically for event volumes (as opposed to hydrographs). This study demonstrates impressive performance from SWMM in estimating event volumes even when uncalibrated. All SWMM simulations had an NSE for drainage and overflow volumes greater than 0.67 which can be considered good to very good model performance (Moriasi et al., 2007). The excellent match of measured drainage and overflow volumes compared to SWMM estimates is also demonstrated in Figure 3.4c & 3.4d.

Table 3.3. Goodness of fit tests for measured drainage and overflow volumes and hydrographs compared to uncalibrated, volume-calibrated and hydrograph-calibrated simulations in DRAINMOD-Urban (DM-Urban) and SWMM.

Goodness of Fit Tests								
		NSE	PBIAS	NSE	PBIAS	d	d_1	E_1
DM-Urban		**Volumes**		**Hydrographs**				
Uncalibrated	Drainage	0.50	41.3	0.39	-1.62	0.88	0.60	0.30
	Overflow	-1.77	72.8	-1.60	-73.01	0.38	0.64	-0.06
Volume-Calibrated	Drainage	0.83	-23.4	0.31	16.7	0.86	0.60	0.32
	Overflow	0.57	-58.4	-1.82	-96.8	0.37	0.64	-0.01
Hydrograph-Calibrated	Drainage	0.83	-46.6	0.60	5.19	0.93	0.75	0.52
	Overflow	0.66	67.0	-0.10	-18.5	0.68	0.74	0.36
SWMM		**Volumes**		**Hydrographs**				
Uncalibrated	Drainage	0.93	20.0	0.25	-17.17	0.90	0.75	0.44
	Overflow	0.73	23.5	0.52	23.53	0.84	0.76	0.47
Volume-Calibrated	Drainage	0.94	16.7	0.41	3.49	0.92	0.76	0.50
	Overflow	0.81	18.0	0.11	-3.64	0.73	0.74	0.38
Hydrograph-Calibrated	Drainage	0.77	38.3	0.42	-37.80	0.92	0.76	0.47
	Overflow	0.67	27.2	0.58	27.24	0.86	0.76	0.48

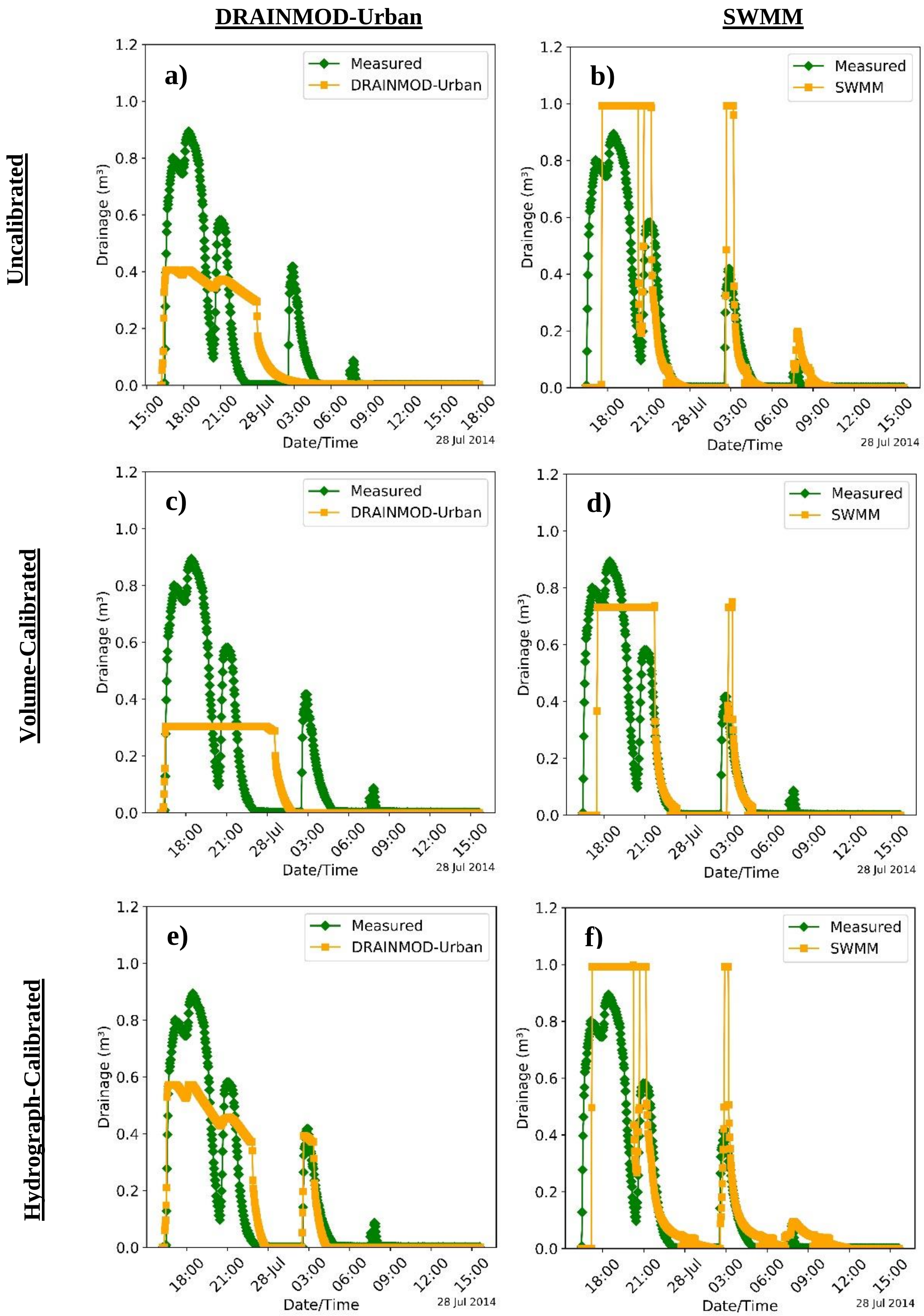


Figure 3.3. Example of modeled and measured drainage hydrographs from both DRAINMOD-Urban and SWMM under three simulations: uncalibrated, volume-calibrated and hydrograph-calibrated.

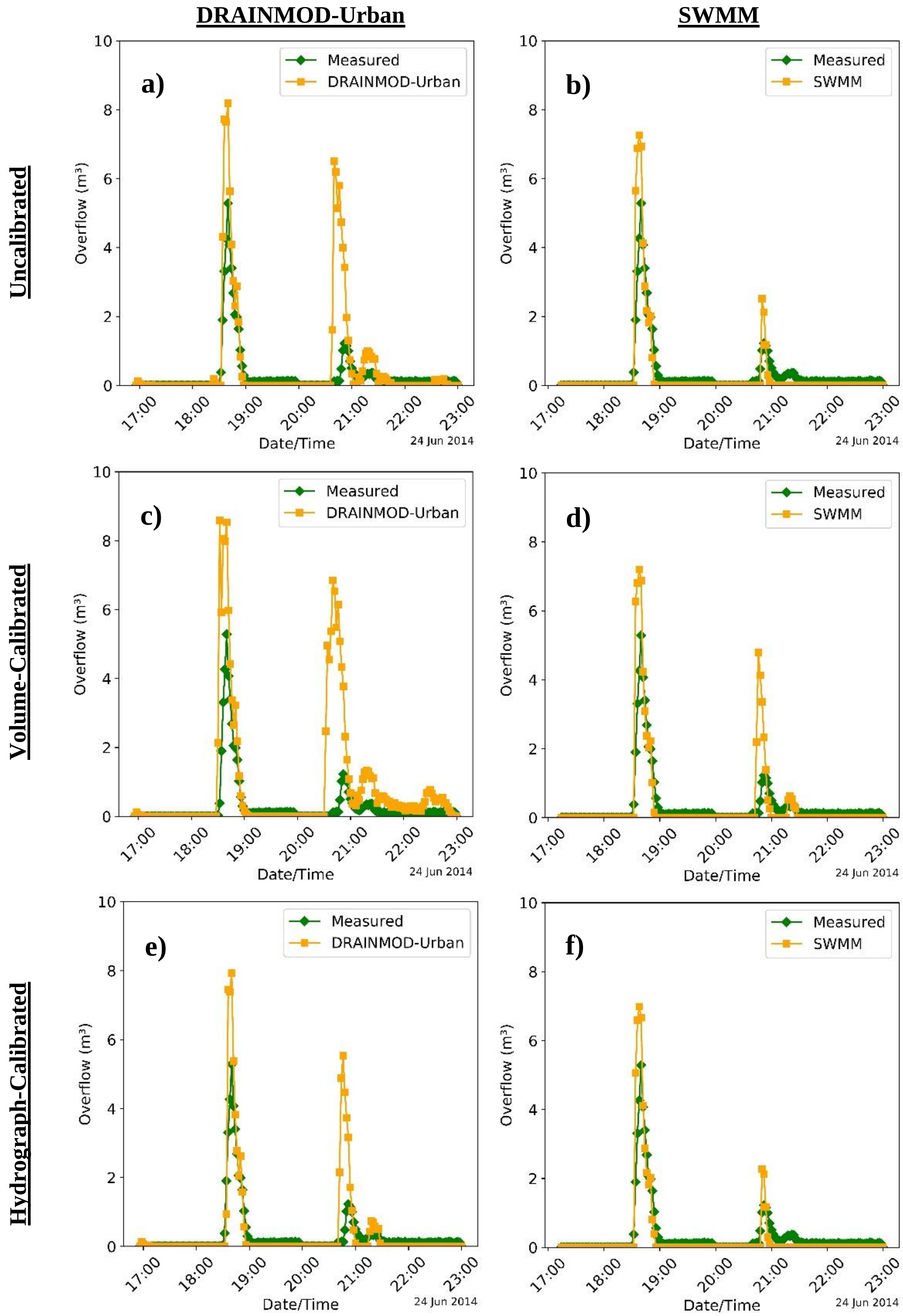


Figure 3.4. Example of modeled and measured overflow hydrographs from both DRAINMOD-Urban and SWMM under three simulations: uncalibrated, volume-calibrated and hydrograph-calibrated.

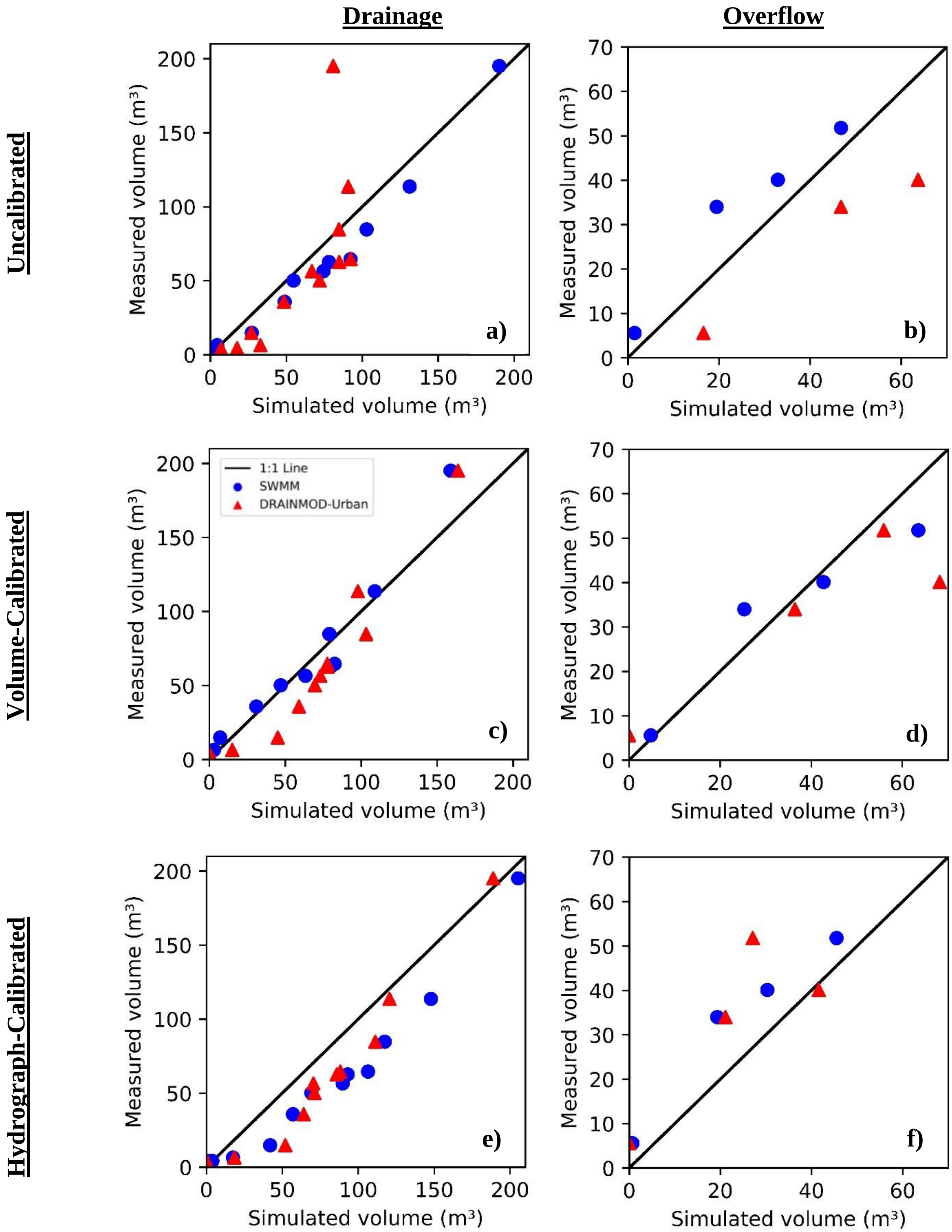


Figure 3.5. Measured and modeled drainage and overflow volumes from both DRAINMOD-Urban and SWMM under three simulations: uncalibrated, volume-calibrated and hydrograph-calibrated.

3.4.3 Comparison of SWMM and DRAINMOD-Urban

3.4.3.1 Hydrograph Performance

Both SWMM and DRAINMOD-Urban are adequate for modeling bioretention with some advantages for each. For drainage hydrographs, a hydrograph-calibrated DRAINMOD-Urban (NSE=0.60) performed better than a hydrograph-calibrated SWMM (NSE=0.42), but for overflow hydrographs, SWMM was stronger (Table 3.3). DRAINMOD-Urban seems to produce better drainage hydrograph shape by visual inspection which was attributed to better timing and response during the first two peaks (Figure 3.3). SWMM produces rectangular hydrographs when the bioretention cell becomes saturated causing K_{sat} and seepage to control the drainage rate. The peak drainage rate could be adjusted in SWMM by adjusting the drainage coefficient or seepage rate, but the rectangular shape was not affected. When the soil layer is saturated, the percolation rate (Eqn. 9) reduces to the K_{sat} and the drainage rate becomes the K_{sat} minus the seepage rate. When the water level meets the top of the storage layer and the soil layer is still unsaturated (but with a soil moisture greater than field capacity), the drainage can be calculated using the HCO parameter (Eqn. 9). This explains the sensitivity of this parameter in SWMM. Although the drainage hydrographs did not show obvious differences as the HCO parameter was changed, the drainage rate at each time step of the rising and falling limbs improved enough to have a significant impact on the cumulative NSE.

SWMM seems to perform better for overflow hydrographs. The peak overflow predicted by SWMM tends to be smaller and closer to the measured peak than DRAINMOD-Urban. It has been shown that peaks have a large effect on the NSE statistic (Broekhuizen et al., 2020; Lisenbee et al., 2020). The calculation of overflow in each model is very similar, simply identifying when the water level exceeds the specified maximum ponding depth and attributing excess to overflow. Therefore, the increased performance of overflow hydrographs in SWMM may be due to the internal soil water distribution that affects the infiltration capacity at the surface.

3.4.3.2 Hydrograph Characteristics

The hydrograph characteristics peak flow, time to peak and event duration were also used to characterize hydrograph performance. The measured and simulated values (SWMM and DRAINMOD-Urban) for each storm were compared against the 1:1 line to find patterns in under and over prediction (Figure 3.6). This was only done for the hydrograph-calibration as that simulation provided drainage and overflow hydrographs closest to measured for both DRAINMOD-Urban and SWMM.

Drainage peak flow shows each model reached a maximum drainage rate (Figure 3.6a). For DRAINMOD-Urban, the maximum drainage rate was 4.8 L/s (or 9.5 cm/hr over the bioretention area) which occurred during events with rainfall depths greater than 42 mm (six out of 12 drainage events). This maximum drainage rate changes with the K_{sat} but is smaller than the K_{sat} used in DRAINMOD-Urban for the bioretention media. For SWMM, the maximum drainage rate was 8.3 L/s which is equal to the measured K_{sat} (16.8 cm/hr). This drainage rate corresponded to rainfall depths greater than 25 mm; therefore, most drainage events (nine out of 12) reached this maximum causing overestimated peaks and rectangular hydrographs. The overflow peak flow has been discussed previously as overestimated by both models but SWMM tended to be closer to measured overflow peaks (Figure 3.6d).

The drainage time to peak was slightly underestimated by both SWMM and DRAINMOD-Urban (Figure 3.6b). The average difference between the time to peak measured and simulated by DRAINMOD-Urban was only 19 minutes with no difference larger than an hour. In SWMM, the average difference in measured and modeled time to peak was 47 minutes with a maximum difference of 3.3 hours. This can be attributed to the truncated peaks in many SWMM drainage hydrographs which reached a maximum drainage flow rate faster than a single peak flow. The time to peak for overflow hydrographs was estimated almost perfectly by both models (Figure 3.6e). The duration of drainage hydrographs seemed to be slightly overpredicted for DRAINMOD-Urban and underpredicted for SWMM, but both had good results compared to measured (Figure 3.6c). For the four overflow hydrographs evaluated, it was difficult to detect a pattern among the duration predicted by DRAINMOD-Urban and SWMM (Figure 3.6f).

3.4.3.3 Volumes

SWMM consistently predicted event volumes better than DRAINMOD-Urban as shown through goodness-of-fit tests with the exception of the drainage volumes of the hydrograph calibration (Table 3.3). The overflow event volumes predicted by SWMM and DRAINMOD-Urban in the hydrograph-calibration were also very similar with NSEs of 0.67 and 0.66 respectively (Table 3.3).

In DRAINMOD-Urban drainage volumes improved as the model was calibrated to match the measured and modeled hydrographs, but in SWMM, drainage volume performance decreases as the hydrograph performance increases. Therefore, the user must decide whether to calibrate SWMM to achieve more accurate volumes or hydrographs but in DRAINMOD-Urban, calibrating to the hydrograph will improve both of the aforementioned factors.

3.4.3.4 Effect of Model Processes on Hydrographs

The differences in hydrographs created by DRAINMOD-Urban and SWMM can be explained by internal processes of the model. The soil water distribution in each model seems to have substantial differences in modeling infiltration through the media, drainage calculations, and representation of the IWS layer.

While DRAINMOD-Urban and SWMM both use the Green-Ampt equation for surface infiltration, SWMM has modified Green-Ampt to account for the effect of ponding (Rossman and Huber, 2016a). Meanwhile, DRAINMOD-Urban accounts for ponding in its soil water distribution procedures (Skaggs et al., 2012). This means that surface infiltration could be very similar if there is adequate infiltration capacity in the rest of the bioretention cell. However, infiltration capacity is determined by how easily water can flow through the soil layer. If this becomes limited, then it will influence ponding and eventually overflow.

For infiltration through the bioretention media, DRAINMOD-Urban uses Green-Ampt with an effective K_{sat} at different water level depths which is recalculated at each time step as the water moves through the soil media. SWMM uses the percolation equation (Eqn. 9) which often is simplified to the K_{sat} when the soil becomes saturated as seen in the truncated drainage hydrographs. The change in water holding capacity in the soil layer affects the rate and amount of water reaching the storage layer and the underdrain.

Once water reaches the underdrain, differences in drainage equations can affect modeled drain output. SWMM tends to overestimate drainage peak flow while DRAINMOD-Urban tends to underestimate drainage peak flow (Figure 3.6). By overestimating the drainage rate in the bioretention cell, SWMM provides more infiltration capacity which can reduce the volume and intensity of water that is converted to overflow.

Finally, another consideration regarding overflow is how the IWS zones are represented in each model. DRAINMOD-Urban simply allows for controlled drainage at a given weir height which directly corresponds to the IWS configuration in the UC cell. The drainage configuration in SWMM had to be adjusted to represent the IWS which increased the storage zone (Figure 3.2). This storage zone has a larger void ratio than the soil porosity which represents the true void space in the IWS zone. Therefore, SWMM can store more water in the IWS zone and it can move more freely causing higher drainage volumes and faster time to peak than DRAINMOD-Urban and measured drainage hydrographs (Figure 3.6). The increase in drainage volumes also leads to a decrease in overflow volumes (Figure 3.5f). Therefore, the water balance could be better represented in SWMM if IWS capabilities were incorporated in the model.

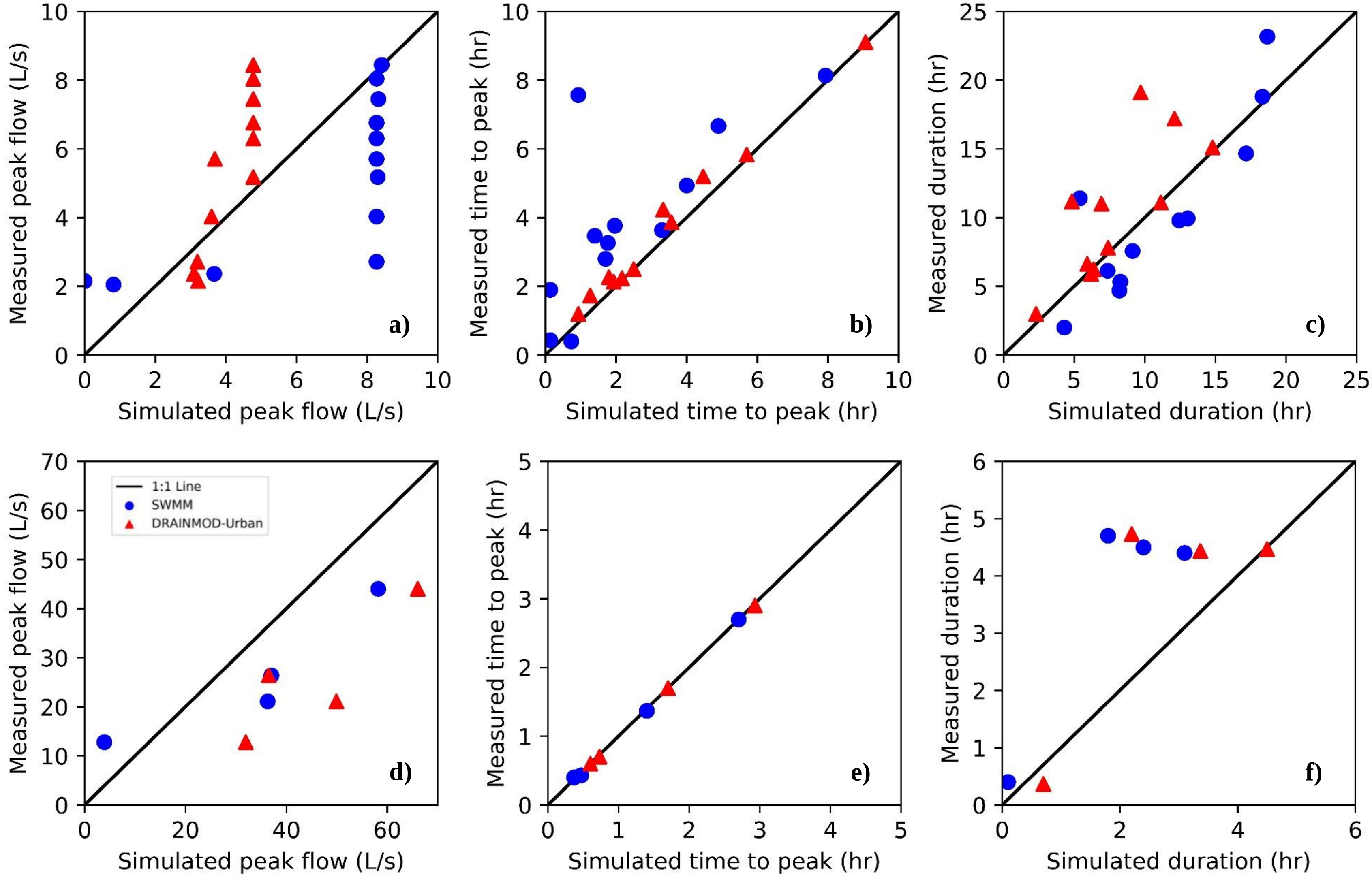


Figure 3.6. Measured hydrograph attributes (peak flow, time to peak and duration) for drainage (a, b, c) and overflow (d, e, f) compared to modeled hydrograph attributes from hydrograph-calibrated DRAINMOD-Urban (DM-Urban, red triangles) and SWMM (blue circles) simulations.

3.5 Summary and Conclusions

This study has shown that the intended application of a bioretention model has a significant impact on model selection and how or if the model is calibrated. If the application is designed to understand the event drainage and overflow volumes from bioretention, then SWMM is a good choice. SWMM is capable of modeling event volumes with good to excellent results in both uncalibrated and calibrated simulations ranging from NSE=0.77 to 0.94 for drainage and NSE=0.67 to 0.81 for overflow.

Both models suffered in performance when attempting to model a high temporal resolution time series, performing much better for aggregated event volumes. However, drainage or overflow hydrographs may be necessary for applications evaluating small time increments or considering flow dynamics such as stream response, combined sewer systems or flooding. The hydrograph-calibrated DRAINMOD-Urban performs better than SWMM for drainage hydrographs which is not surprising when comparing the drainage equations employed by each model. SWMM performs better than DRAINMOD-Urban for overflow hydrographs primarily by more closely predicting overflow event peak flow durations.

DRAINMOD-Urban benefits more from calibration of the drainage and overflow hydrographs compared to SWMM. Interestingly, in SWMM, calibration of one objective (event volumes or hydrographs), leads to diminished performance of the other objective. This introduces a choice for SWMM users: are volumes or hydrographs are more important for drainage and/or overflow given the application? For DRAINMOD-Urban, the hydrograph-calibration improves both the volumes and hydrographs of drainage and overflow eliminating a decision between better predicted volumes or hydrographs.

If a choice between drainage and overflow hydrographs must be made, we assert that, in most applications, better drainage hydrographs will give a better understanding of if the bioretention cell is working properly and how it behaves under various storm characteristics given that drainage volumes are also accurately represented. The overflow from a bioretention cell can be managed in various ways from seeping into surrounding soil to being routed to a storm drain and often are combined with drainage when leaving the bioretention cell; therefore, overflow volumes may be sufficient depending on the bioretention cell design.

Next steps require more calibration studies of bioretention systems for both DRAINMOD-Urban and SWMM, especially with more than four overflow events. More overflow events need to be analyzed to improve the confidence of statistical conclusions about overflow performance in each model. This study only considered one bioretention cell but more need to be modeled to understand how these models behave across a variety of conditions such as storm size, drainage configurations, and other bioretention design features. Sensitivity analysis could also improve understanding of how measurement or estimation of model inputs affect the accuracy of output hydrographs.

Simulating accurate drainage and overflow hydrographs would be useful in a number of applications that explore urban flow dynamics and its connection to natural hydrology. Hydrographs give much more information on the timing and intensity of flows as opposed to just volumes. This is especially useful in watershed studies. SWMM is often used for watershed-scale studies of LID practices which are often uncalibrated or calibrated to total surface runoff, but the performance of individual LID practices is ignored. This study not only calibrated SWMM to field data, but also challenged the performance of SWMM with regard to outputs from a single bioretention cell. Individual bioretention cell performance is important in scenarios such as treatment trains, where the outflow of one treatment system serves as inflow to another, and to avoid discrepancies in outflow hydrographs that can lead to significant errors across the watershed. This could also be the case in combined sewer systems where disagreements in modeled and measured outflow could lead to misrepresentation of the available flow capacity in the sewer pipe during a storm event. DRAINMOD-Urban is not a watershed-scale model, but it could be utilized as an add-on tool for SWMM. The improved drainage hydrographs from DRAINMOD-Urban and the runoff generation, routing, and other LID components in SWMM combined into a single model would be a big step in accurately representing bioretention cells at a watershed scale.

3.6 References

Akan, A.O. (2013) Preliminary Design Aid for Bioretention Filters. Journal of Hydrologic Engineering 18(3), 318-323. https://doi.org/10.1061/(asce)he.1943-5584.0000554

Avellaneda, P.M., Jefferson, A.J., Grieser, J.M. and Bush, S.A. (2017) Simulation of the Cumulative Hydrological Response to Green Infrastructure. Water Resources Research 53(4), 3087-3101. https://doi.org/10.1002/2016wr019836

Barbu, I.A. and Ballestero, T.P. (2015) Unsaturated Flow Functions for Filter Media Used in Low-Impact Development—Stormwater Management Systems. Journal of Irrigation and Drainage Engineering 141(1), 04014041. https://doi.org/10.1061/(asce)ir.1943-4774.0000766

Bosley, E.K. (2008) Hydrologic Evaluation of Low Impact Development Using a Continuous, Spatially-Distributed Model.

Broekhuizen, I., Leonhardt, G., Marsalek, J. and Viklander, M. (2020) Event Selection and Two-Stage Approach for Calibrating Models of Green Urban Drainage Systems. Hydrol. Earth Syst. Sci. 24(2), 869-885. https://doi.org/10.5194/hess-24-869-2020

Brown, R.A. (2011) Evaluation of Bioretention Hydrology and Pollutant Removal in the Upper Coastal Plain of North Carolina with Development of a Bioretention Modeling Application in DRAINMOD. Doctoral dissertation, North Carolina State University, Raleigh, North Carolina.

Brown, R.A. and Hunt, W.F. (2011) Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells. Journal of Irrigation and Drainage Engineering 137(3), 132-143. https://doi.org/10.1061/(Asce)Ir.1943-4774.0000167

Brown, R.A. and Hunt, W.F. (2012) Improving Bioretention/Biofiltration Performance with Restorative Maintenance. Water Science and Technology 65(2), 361-367. https://doi.org/10.2166/wst.2012.860

Brown, R.A., Skaggs, R.W. and Hunt, W.F. (2013) Calibration and Validation of DRAINMOD to Model Bioretention Hydrology. Journal of Hydrology 486, 430-442. https://doi.org/10.1016/j.jhydrol.2013.02.017

Davis, A.P. (2008) Field Performance of Bioretention: Hydrology Impacts. Journal of Hydrologic Engineering 13(2), 90-95. https://doi.org/10.1061/(Asce)1084-0699(2008)13:2(90)

Davis, A.P., Hunt, W.F., Traver, R.G. and Clar, M. (2009) Bioretention Technology: Overview of Current Practice and Future Needs. Journal of Environmental Engineering 135(3), 109-117. https://doi.org/10.1061//ASCE/0733-9372/2009/135:3/109

Davis, A.P., Traver, R.G., Hunt, W.F., Lee, R., Brown, R.A. and Olszewski, J.M. (2012) Hydrologic Performance of Bioretention Storm-Water Control Measures. Journal of Hydrologic Engineering 17(5), 604-614. https://doi.org/10.1061/(Asce)He.1943-5584.0000467

Dietrich, A., Yarlagadda, R. and Gruden, C. (2017) Estimating the Potential Benefits of Green Stormwater Infrastructure on Developed Sites Using Hydrologic Model Simulation. Environmental Progress & Sustainable Energy 36(2), 557-564. https://doi.org/10.1002/ep.12428

DRAINMOD 6.1 Help File (2013), North Carolina State University.
Elliott, A. and Trowsdale, S. (2007) A Review of Models for Low Impact Urban Stormwater Drainage. Environmental Modelling & Software 22(3), 394-405. https://doi.org/10.1016/j.envsoft.2005.12.005
EPA SWMM Help File 5.1 (2017), U.S. Environmental Protection Agency,, Washington, DC.
Gulbaz, S. and Kazezyilmaz-Alhan, C.M. (2017) An Evaluation of Hydrologic Modeling Performance of EPA SWMM for Bioretention. Water Sci Technol 76(11), 3035-3043. https://doi.org/10.2166/wst.2017.464
Hathaway, J.M., Brown, R.A., Fu, J.S. and Hunt, W.F. (2014) Bioretention Function under Climate Change Scenarios in North Carolina, USA. Journal of Hydrology 519, 503-511. https://doi.org/10.1016/j.jhydrol.2014.07.037
Hunt, W.F., Jarrett, A.R., Smith, J.T. and Sharkey, L.J. (2006) Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. Journal of Irrigation and Drainage Engineering 132(6), 600-608. https://doi.org/10.1061/(Asce)0733-9437(2006)132:6(600)
Kaykhosravi, S., Khan, U. and Jadidi, A. (2018) A Comprehensive Review of Low Impact Development Models for Research, Conceptual, Preliminary and Detailed Design Applications. Water 10(11), 1541. https://doi.org/10.3390/w10111541
Li, C., Fletcher, T.D., Duncan, H.P. and Burns, M.J. (2017) Can Stormwater Control Measures Restore Altered Urban Flow Regimes at the Catchment Scale? Journal of Hydrology 2017 v.549, pp. 631-653. https://doi.org/10.1016/j.jhydrol.2017.03.037
Li, Z.Y. and Lam, K.M. (2015) Statistical Evaluation of Bioretention System for Hydrologic Performance. Water Science and Technology 71(11), 1742-1749. https://doi.org/10.2166/wst.2015.131
Lisenbee, W., Hathaway, J., Negm, L., Youssef, M. and Winston, R. (2020) Enhanced Bioretention Cell Modeling with DRAINMOD-Urban: Moving from Water Balances to Hydrograph Production. Journal of Hydrology 582, 124491. https://doi.org/https://doi.org/10.1016/j.jhydrol.2019.124491
Liu, J., Sample, D., Bell, C. and Guan, Y. (2014) Review and Research Needs of Bioretention Used for the Treatment of Urban Stormwater. Water 6(4), 1069-1099. https://doi.org/10.3390/w6041069
Liu, R.F. and Fassman-Beck, E. (2017) Hydrologic Experiments and Modeling of Two Laboratory Bioretention Systems under Different Boundary Conditions. Frontiers of Environmental Science & Engineering 11(4). https://doi.org/ARTN 1010.1007/s11783-017-0951-5
Lucas, W. (2010) Design of Integrated Bioinfiltration-Detention Urban Retrofits with Design Storm and Continuous Simulation Methods. J. Hydrol. Eng. 15(6), 486-498. https://doi.org/10.1061//ASCE/HE.1943-5584.0000137
Lynn, T.J., Nachabe, M.H. and Ergas, S.J. (2018) Swmm5 Unsaturated Drainage Models for Stormwater Biofiltration with an Internal Water Storage Zone. Journal of Sustainable Water in the Built Environment 4(1), 04017018. https://doi.org/10.1061/jswbay.0000844

McCutcheon, M. and Wride, D. (2013) Shades of Green: Using SWMM Lid Controls to Simulate Green Infrastructure. Journal of Water Management Modeling. https://doi.org/10.14796/jwmm.r246-15

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L. (2007) Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Transactions of the ASABE 50(3), 885-900. <Go to ISI>://WOS:000248036800021

Olszewski, J.M. and Davis, A.P. (2013) Comparing the Hydrologic Performance of a Bioretention Cell with Predevelopment Values. Journal of Irrigation and Drainage Engineering 139(2), 124-130. https://doi.org/10.1061/(Asce)Ir.1943-4774.0000504

Rosa, D.J., Clausen, J.C. and Dietz, M.E. (2015) Calibration and Verification of SWMM for Low Impact Development. Journal of the American Water Resources Association 51(3), 746-757. https://doi.org/10.1111/jawr.12272

Rossman, L.A. (2010) Modeling Low Impact Development Alternatives with SWMM. Journal of Water Management Modeling. https://doi.org/10.14796/jwmm.r236-11

Rossman, L.A. and Huber, W.C. (2016) Storm Water Management Model Reference Manual Volume Iii – Water Quality. Division, O.o.R.a.D.W.S.a.W.R. (ed), National Risk Management Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cinncinati, OH.

Saxton, K.E. and Rawls, W.J. (2006) Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. Soil Science Society of America Journal 70(5), 1569. https://doi.org/10.2136/sssaj2005.0117

Skaggs, R.W., Youssef, M.A. and Chescheir, G.M. (2012) Drainmod: Model Use, Calibration, and Validation. Transactions of the ASABE 55(4), 1509-1522. <Go to ISI>://WOS:000309089900030

Sun, Y.-w., Li, Q.-y., Liu, L., Xu, C.-d. and Liu, Z.-p. (2014) Hydrological Simulation Approaches for Bmps and Lid Practices in Highly Urbanized Area and Development of Hydrological Performance Indicator System. Water Science and Engineering 7(2), 143-154. https://doi.org/10.3882/j.issn.1674-2370.2014.02.003

Sun, Y.-w., Wei, X.-m.C. and Pomeroy, C.A. (2011) Global Analysis of Sensitivity of Bioretention Cell Design Elements to Hydrologic Performance. Water Science and Engineering, 4(3), 246-257. https://doi.org/10.3882/j.issn.1674-2370.2011.03.002

Tiveron, T., Gholamreza-Kashi, S. and Joksimovic, D. (2018) A Usepa SWMM Integrated Tool for Determining the Suspended Solids Reduction Performance of Bioretention Cells. Journal of Water Management Modeling 26. https://doi.org/Artn C44310.14796/Jwmm.C443

Winston, R.J. (2015) Resilience of Green Infrastructure under Extreme Conditions. Doctoral dissertation.

Winston, R.J., Dorsey, J.D. and Hunt, W.F. (2016) Quantifying Volume Reduction and Peak Flow Mitigation for Three Bioretention Cells in Clay Soils in Northeast Ohio. Sci Total Environ 553, 83-95. https://doi.org/10.1016/j.scitotenv.2016.02.081

CHAPTER IV

PEDOTRANSFER FUNCTIONS FOR ESTIMATING SOIL PARAMETERS IN BIORETENTION MODELING: A SENSITIVITY STUDY

4.1 Abstract

As bioretention has become a leading stormwater management practice, more attention has been given to models developed for these systems. DRAINMOD-Urban is a recently developed model shown to perform well for simulating hydrographs of hydrologic pathways in a bioretention cell. One advantage of this model is the use of the soil-water characteristic curve (SWCC) which provides better analysis of soil moisture conditions within a bioretention cell than more simplified methods used in other bioretention models. However, obtaining the SWCC and other required soil parameters for DRAINMOD-Urban requires time- and labor-intensive laboratory tests of the bioretention media. To circumvent these soil testing procedures, pedotransfer functions (PTF) can be used to derive the SWCC and saturated hydraulic conductivity (K_{sat}) from more easily obtained soil properties such as texture and bulk density. Two PTFs, ROSETTA (Schaap et al., 2001) and Vereecken et al. (1989), have shown good performance for coarse-textured soils. These were chosen to compare PTF-derived SWCCs to the measured SWCC within the context of modeling a bioretention cell in DRAINMOD-Urban. K_{sat} was also investigated for calibrated, measured and ROSETTA values to determine if K_{sat} measurement was necessary for predicting bioretention cell processes with DRAINMOD-Urban. Across all scenarios, the calibrated K_{sat} and measured SWCC provided the best model performance of drainage and overflow hydrographs (drainage: NSE=0.60, PBIAS=5.2; overflow: NSE=-0.10, PBIAS=-18.5) but the calibrated K_{sat} and ROSETTA PTF-derived SWCC was a close second in drainage (NSE=0.59, PBIAS=22.5) with slightly better overflow results (NSE=-0.06, PBIAS=3.5).

This confirms that a calibrated DRAINMOD-Urban can perform equally well with a SWCC that is measured and calculated using the ROSETTA PTF. The calibrated K_{sat} performed best but the measured and ROSETTA K_{sat} performed similarly in DRAINMOD-Urban. These results suggest that time-consuming soil measurements can be eliminated when modeling bioretention cells with DRAINMOD-Urban in favor of PTFs. Understanding of the sensitivity of the SWCC, K_{sat}, and other calibration parameters in DRAINMOD-Urban would enhance this study. More studies are also needed that investigate additional PTFs, field study sites, and bioretention models.

4.2 Introduction

As stormwater management has evolved over the last few decades, green infrastructure practices like bioretention have become widely implemented to reduce stormwater runoff volumes and peak flow. As application of these systems has grown, bioretention modeling has been developed to allow designers to test proposed designs, provide guidance for design standards, and estimate runoff reduction potential. Currently, many hydrologic/hydraulic models provide bioretention modeling capabilities (Ch. 1).

However, existing models are often use simplified representations of bioretention cells that do not fully account for fundamental hydrologic processes. Many bioretention models use Green-Ampt infiltration that assumes saturation although bioretention cells are rarely saturated (Barbu and Ballestero, 2015; Akan, 2013; Brown et al., 2013b). Others lacked the ability to represent key design and performance features such as underdrains, internal water storage (IWS) zones, soil-moisture accounting, and evapotranspiration (ET) calculations. To model bioretention, there are a wide variety of soil inputs required which can influence important hydrologic pathways such as infiltration (Ch. 1). Often default values for soil properties based on soil texture are provided in hydrologic models in the case that measured values are unavailable. Many bioretention modeling studies to date were reviewed in Chapter 1 to understand the hydrologic processes of each model.

DRAINMOD was originally developed to simulate poorly-drained agricultural soils but more recently has been applied to bioretention, showing the ability to simulate drainage and IWS among other important design features (Winston, 2015; Hathaway et al., 2014; Brown et al., 2013b). Brown et al. (2013b) first used DRAINMOD to model four bioretention cells in North Carolina with good calibration results across all hydrologic pathways (NSE=0.71-0.94). DRAINMOD was also calibrated to three more bioretention cells in Ohio with good agreement of measured volumes for each water balance component (NSE>0.7; Winston, 2015). While these studies showed good calibration to measured volumes of the water balance for individual storm events, the model was unable to output data at a time scale fine enough to describe the outflow hydrographs from a bioretention cell. To remedy this, DRAINMOD-Urban was developed by reducing input and output timesteps to 1-minute intervals. Lisenbee et al. (2020, Ch. 2) evaluated the performance of DRAINMOD-Urban and determined it to be well suited to bioretention modeling by producing output hydrographs that have good agreement with measured values (NSE=0.60) and event volumes that are close to measured volumes (NSE=0.83).

DRAINMOD-Urban uses the soil-water characteristic curve (SWCC) and the saturated hydraulic conductivity (K_{sat}) to estimate soil-water processes based on water level fluctuations in the bioretention cell. Brown et al. (2013) asserts that the SWCC provides much better analysis of soil moisture conditions within a bioretention cell than estimations of water storage capacity used in other bioretention models that assume either a constant void ratio or the volume of saturation minus field capacity. However, obtaining the SWCC and K_{sat} requires lengthy soil laboratory tests. Much variability exists in both parameters, so it is suggested that multiple samples from a given bioretention cell be analyzed to address spatial variability (Ahmed et al., 2015). K_{sat} has been shown to vary widely up to three orders of magnitude with associated high skewness from various field studies (Garcia-Gutierrez et al., 2018; Papanicolaou et al., 2015; Gwenzi et al., 2011; Warrick and Nielsen, 1980) and specifically in rain gardens (Asleson et al., 2009).

4.2.1 Pedotransfer Functions

Many soil hydraulic properties are difficult to measure with field or laboratory methods. Soil sampling, handling, and testing can introduce human and measurement errors which require multiple samples to reduce uncertainty (Reynolds et al, 2000; Pedescoll et al., 2011). Furthermore, many measurement techniques for SWCC and K_{sat} can be very time-consuming. Therefore, there has been significant effort to describe soil hydraulic properties based on easily measured soil characteristics such as soil texture, organic matter (OM), and bulk density (BD). Some studies have simply estimated average soil hydraulic properties (soil suction, field capacity, wilting point, K_{sat}, etc.) for each soil textural class (Schaap and Leij, 1998; Wosten et al., 1995; Carsel and Parrish, 1988; Rawls and Brakensiek, 1982) based on large soil datasets. This is often used to guide users in hydrologic models such as in SWMM and RECARGA which use soil properties estimated by Rawls et al. (1998).

Another option is to use pedotransfer functions (PTF) or empirical equations that associate easily measurable soil properties such as texture, organic matter (OM), and bulk density (BD) with more complicated soil properties such as the SWCC and K_{sat}. For example, PTFs have been used to estimate hydraulic conductivity from soil properties or the measured SWCC (Mualem, 1977) and to predict soil hydraulic properties from soil texture (Saxton et al., 1986). Empirical PTFs can be split into point PTFs and parametric PTFs. Point PTFs use soil properties to estimate water content at a single matric potential such as that associated with field capacity (33 kPa) and permanent wilting point (1500 kPa). Parametric PTFs relate soil properties to analytical expressions such as Brooks and Corey (BC, 1966), van Genuchten (VG, 1980), and Campbell (1974) which are often used for deriving a SWCC, also called a water retention curve (Patil and Singh, 2016; Liao et al., 2011). Patil and Singh (2016) noted commonalities with all PTFs reviewed. All PTFs used either the BC or VG functions, included clay content and either sand or silt content as an input variable, and had improved performance with the inclusion of BD.

An alternative to empirical PTFs are physicoempirical PTFs which describe the empirical relationship between the measured particle size distribution (PSD) and the physical pore-size distribution of a soil. Barbu and Ballestero (2015) employed the Arya-Paris (1981) physicoempirical PTF to develop a methodology for modeling unsaturated flow conditions for bioretention media. Although this model has been shown to work well for sandy soils, it requires a detailed particle size distribution and more in-depth calculations than other purely empirical PTFs (Tietje and Tapkenhinrichs, 1993). The Arya-Paris model also was developed over a small range of soil textures and therefore does not perform well when extrapolating to other soils (Tietje and Tapkenhinrichs, 1993, Cornelis et al., 2001).

Indeed, researchers are warned that because PTFs are empirical, extrapolation beyond soil types used to develop the PTFs could require validation or development of site-specific PTFs (Patil and Singh, 2016). Due to a lack of large soil databases, generic PTFs that can be applied to a wide range of soils are rare. However, the Vereecken PTF was developed over a wide range of soils and has shown good performance over a variety of soil textures, although coarse-textured soils are better represented (Tietje and Tapkenhinrichs, 1993; Wagner et al., 1998; Cornelis et al., 2001). Additionally, the ROSETTA PTF program (Schaap et al., 2001) is a common generic PTF that has been calibrated and validated for many soil types across multinational soil databases (Patil and Singh, 2016; Wosten et al., 2001).

4.2.2 Objective

As bioretention models necessarily become more complex to truly represent urban hydrologic processes, soil inputs play an important role in these processes which might necessitate complex soil measurements. This study poses the question: can pedotransfer functions be used as substitutes for DRAINMOD-Urban soil inputs, the SWCC and K_{sat}, to avoid time-consuming soil laboratory procedures? To answer this question, our objective was to delve into the necessary soil properties required for accurate representation of bioretention by comparing performance of DRAINMOD-Urban to measured outflow volumes and hydrographs using measured soil properties and those developed by pedotransfer functions.

4.3 METHODS

4.3.1 Site Descriptions

The Ursuline College (UC) bioretention cell was used for model simulations using either measured soil properties or PTFs. The UC cell was 182 m^2 and was designed to treat stormwater runoff from a 3600 m^2 drainage area. A parking lot comprised most of the 77% of impervious surfaces in the drainage area. This cell was previously calibrated in DRAINMOD-Urban (Lisenbee et al., 2020, Ch. 2). Details on monitoring equipment used at this site can be found in Winston et al., 2016. Briefly, a tipping bucket rain gauge measured precipitation on-site at 1-minute intervals. The inflow to the bioretention cell was calculated in SWMM as the runoff from the drainage area. The sum of drainage and overflow was measured every two minutes with a 60-degree, sharp-crested, v-notch weir, and a Hobo U20 pressure transducer. These two flows were separated in SWMM using a rating curve based on the measured internal water level to distinguish 12 events with drainage and four with overflow (Winston et al., 2016). A diagram of the UC cell is reprinted below for convenience (Figure 4.1).

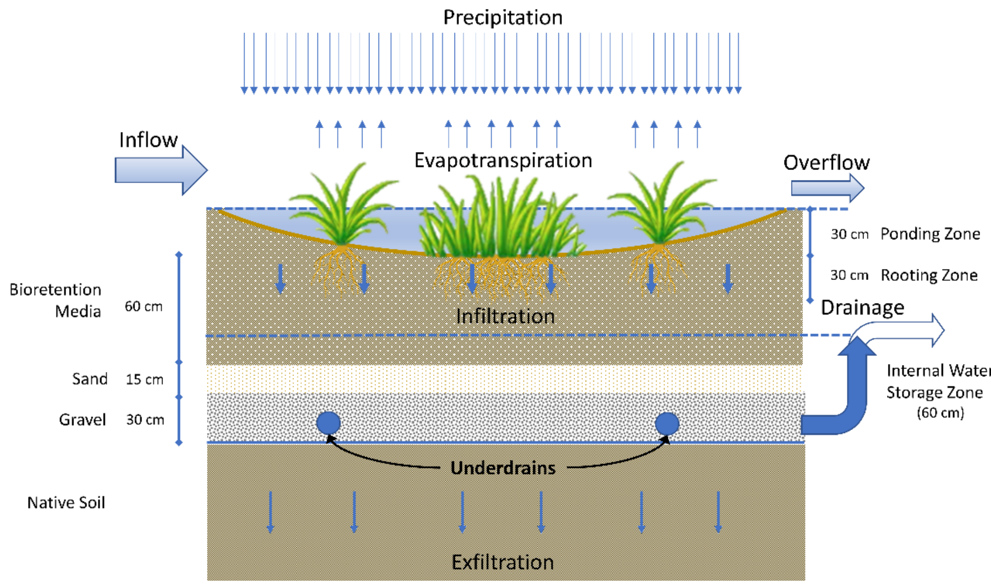


Figure 4.1. Schematic of Ursuline College (UC) bioretention cell.

4.3.2 Measured Soil Properties

The measured soil properties are important in this study to provide a standard for comparison against the PTFs. The soil particle size distribution, to determine media composition and soil textural class, was determined using sieve methods (ASTM, 2007). The organic matter fraction of the fill media was measured through loss-on ignition methods (ASTM, 2014). The organic carbon fraction was not measured but was estimated as 50% of the total organic matter (Pribyl, 2010). Constant head permeability tests were conducted on triplicate 75 mm soil cores of the bioretention media to find the K_{sat} using the methods outlined by Klute (1986). Lastly, triplicate cores of the bioretention media were used to find the average measured SWCC (Appendix A) using a pressure plate apparatus to determine the water drained from an initially saturated sample under various matric potentials (Klute, 1986). These soil cores were also used to find the bulk density of the soil as the dry mass for a given volume (ASTM, 2018). A summary of measured soil properties describing the UC bioretention media can be found in Table 4.1.

Table 4.1. Summary of measured soil properties of the bioretention media in the Ursuline College (UC) cell. BD=Bulk Density, OM=Organic Matter, OC=Organic Carbon, K_{sat}=Saturated Hydraulic Conductivity (cm/hr). OC is calculated as 50% of OM according to Pribyl (2010).

Sand (%)	87
Silt (%)	4
Clay (%)	9
BD (g/cm3)	1.5
OM (%)	4.3
OC (%)	2.2
K_{sat} (cm/hr)	16.8

Measured Soil Moisture

Volumetric soil moisture was measured in the UC cell using time domain reflectometer (TDR) probes at 15, 30, 60, and 90 cm depths. The 15 and 30 cm depths described the bioretention media whereas the 60 and 90 cm depths described moisture in the internal water storage (IWS) and sand/gravel storage zones (Figure 4.1). These data were calibrated using the moisture content at field capacity (0.201 cm^3/cm^3) determined from the SWCC at 10 kPa. Field capacity is often associated with a matric potential of 33 kPa but for coarse-textured soils, it has been measured at a lower matric potential such as 10 kPa (Nemes et al., 2011; Kirkham, 2005; Pachepsky and Rawls, 2004; Richards and Weaver, 1944). Field capacity in the measured soil moisture data was determined through visual identification of the moisture content at which the falling limb changes slope (Zotarelli et al., 2010). The soil moisture at this point was set to 0.201 cm^3/cm^3 and measured soil moisture was adjusted relative to field capacity. The range and frequency of soil moisture in the UC cell was identified through histograms at each measured depth.

4.3.3 PTF Selection and Calculation

In our study, two PTFs, ROSETTA (Schaap et al., 2001) and Vereecken et al. (1989), were chosen to compare to the measured SWCC for use in DRAINMOD-Urban. These parametric PTFs are well-suited to developing an entire moisture content profile (i.e., the SWCC) for use in DRAINMOD-Urban. The first PTF, ROSETTA, is a promising generic PTF developed by the USDA based on a wide range of soil samples from the United States and Europe. ROSETTA uses empirical equations developed to describe the relationship between VG parameters and increasing levels of inputs from basic soil properties. ROSETTA is also capable of computing saturated and unsaturated hydraulic conductivity using the van Genutchen-Mualem method (van Genuchten, 1980). The second PTF, the Vereecken equation, has been noted to perform well for coarse-grained soils (Tietje and Tapkenhinrichs, 1993; Wagner et al., 1998; Cornelis et al., 2001). It uses nonlinear regression relationships to relate percent sand, percent clay, bulk density and organic carbon to the VG parameters. More information about each of these PTFs is described in the following sections. For the remainder of the document, the PTF from ROSETTA (Schaap et al., 2001) and the Vereecken et al. (1989) will be referred to as the ROSETTA PTF and Vereecken PTF, respectively.

4.3.3.1 ROSETTA PTF

Multiple PTFs were developed by Schaap et al. (1998) and Schaap and Leij (1998) using neural network models from 2134 water retention samples and 1306 K_{sat} samples across primarily subtropical North American and European soils. Later, the ROSETTA computer program was developed with these PTFs to allow users to easily compute parameters used in the van Genuchten (VG) equation to develop the water retention curve or SWCC:

$$h = \alpha^{-1}\left[\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{\frac{-1}{m}} - 1\right]^{\frac{1}{n}} \qquad \text{Eqn. 1}$$

where h is the soil water pressure head (cm), θ_s is the saturated water content (cm^3/cm^3), θ_r is the residual water content (cm^3/cm^3), and α, n, and m are empirical parameters. In ROSETTA, it is assumed that m=-1/(n-1). The saturated hydraulic conductivity is estimated in ROSETTA using neural network models of 1306 K_{sat} samples from the same databases as used for the water retention samples (Schaap et al., 1998; Schaap and Leij, 1998).

A unique feature of the ROSETTA program is that is uses a bootstrapping method to account for uncertainty around each of the calculated VG parameters. ROSETTA uses a system of hierarchical PTFs or different empirical equations to calculate the VG parameters based on different levels of input data available. It offers PTFs for generic soil texture (TXT), percent sand, silt, and clay (SSC), percent sand, silt, and clay plus bulk density (SSCBD), and the addition of water contents at field capacity (33 kPa) and permanent wilting point (1500 kPa) which are labeled SSCBDθ_{33} and SSCBD$\theta_{33}\theta_{1500}$ respectively. In the initial ROSETTA calibration, the R^2 of both the water retention parameters and the K_{sat}

increased as additional input parameters were added (Schaap et al, 2001). It was also noted that the TXT and SSC methods provided similar results.

Rubio et al. (2008) compared water retention parameters developed by all variations of the ROSETTA PTFs to PTFs developed for site-specific soils which were high in silt and clay content (>75%). Although these soils were very different from bioretention soils, this study validated the results found by Schaap et al. (2001). The SSCBD$\theta_{33}\theta_{1500}$ simulation provided the best results from ROSETTA although it still overestimated the moisture content near field capacity and underestimated moisture content near permanent wilting point and saturation. However, the error near field capacity was less than near saturation or wilting point. Similarly, Alvarez-Acosta et al. (2012) investigated the K_{sat} from all hierarchical levels of ROSETTA (i.e. number of inputs required) for clay loam, sandy clay loam, and sandy clay soils. Even among similar soil textures, the measured K_{sat} had high variability. The ROSETTA SSCBD$\theta_{33}\theta_{1500}$ K_{sat} best matched measured K_{sat}.

Further studies have used ROSETTA PTFs to derive the K_{sat} required in hydrologic models. Specific to this study, the DRAINMOD help file suggests ROSETTA as a valid method for approximation of required soil inputs when measured values are unavailable. Salazar et al. (2008) tested this assertion and concluded that for coarse-texted soils, the ROSETTA PTF-estimated K_{sat} values used in DRAINMOD simulated drainage outflow volumes as accurately as laboratory-measured K_{sat} values. Likewise, Sobieraj et al. (2001) used the measured K_{sat} and the predicted K_{sat} from the ROSETTA SSC and ROSETTA SSCBD PTFs in the TOPOG-SBM model (a Simple Bucket Model) to compare runoff hydrographs and overland flow frequency. The runoff hydrographs with the ROSETTA SSC

K_{sat} overpredicted the total and peak runoff. Meanwhile, the simulations with K_{sat} from the ROSETTA SSCBD PTF created runoff hydrographs most similar to observed hydrographs for 35% of events. Overall, in this study, model simulations with a ROSETTA SSC K_{sat} performed poorly, but when bulk density was added (SSCBD), it performed similarly to simulations with a measured K_{sat}.

4.3.3.2 Vereecken PTF

Vereecken et al. (1989) used nonlinear regression analysis to fit easily identified soil characteristics to the parameters required for the VG model based on 182 soil textures from Belgian soils. However, in the Vereecken model the VG equation (Eqn. 1) is assumed to have an m=1. The regression equations developed in this model require the percent clay content, percent sand content, bulk density, and percent organic carbon content. Although organic carbon is not always tested on soil, relationships from 24 empirical studies suggest a correlation with organic matter at a ratio of 1.7-2.0 organic matter to organic carbon (Pribyl, 2010). Vereecken et al. (1990) used similar methods to develop a PTF for K_{sat}, but it was not used in this study due to verification studies that indicate an overestimation of K_{sat} with this PTF (Tietje and Hennings, 1995; Wagner et al., 2001)

The Vereecken PTF has been used in a number of validation studies for PTFs with good results due to the wide range of soils used to develop the Vereecken PTF. Wagner et al., 1998 compared the Vereecken PTF to two other PTF regression models for six German soils. The Vereecken PTF performed well in comparison to measured water retention with an R^2=0.82 and showed increased performance for coarse soil textures. Espino et al. (1996)

compared soil moisture, pressure head, and drainage flux outputs from the SWATRER model determined using either measured moisture retention, or that derived from Vereecken PTFs. In this study, the Vereecken PTF produced larger moisture contents and drainage volumes than the measured SWCC. Tietje and Tapkenhinrichs (1993) describes the Vereecken PTF as the most accurate of the 13 PTFs studied because it was applicable to a wide range of soil samples with low error, including those with high organic matter. This could be due to the inclusion of organic carbon as a predictor variable.

Another detailed validation study of nine PTFs (including point and parametric) considered the Vereecken PTF to be the most accurate (Cornelis et al., 2001). Specifically, in comparison to the measured SWCC, the Vereecken PTF showed the best values over the other eight PTFs for three complementary statistical indices: the mean difference (MD), the root of the mean squared difference (RMSD), and the Pearson correlation coefficient (r). When all nine PTFs were evaluated by soil textural class, the Vereecken PTF showed the best RMSD for coarse-textured soils (sand, loamy sand, and sandy loam) (Cornelis et al., 2001). The performance of the Vereecken PTF in validation studies, especially for coarse-textured soils, suggests that it could also perform well for bioretention media.

4.3.4 DRAINMOD-Urban Methodology

DRAINMOD-Urban has recently been used for bioretention modeling to predict high temporal resolution drainage and overflow hydrographs, an upgrade from the previous model version (DRAINMOD) that could only calculate drainage and overflow volumes at a coarse daily scale (Brown et al., 2013; Winston, 2015; Lisenbee et al., 2020). DRAINMOD-Urban is a long-term continuous simulation model that can operate on 1-minute time steps to simulate the flashy nature of urban runoff. DRAINMOD-Urban requires 1-minute resolution precipitation and inflow input files. Other climate inputs include a user-defined potential evapotranspiration (PET) file or temperature files used to calculate PET using the Thornthwaite method. Rooting depth is required to evaluate the soil depth at which water uptake can occur. Drainage design parameters are used to define the depth of each layer in the bioretention cell and the drainage configuration. Seepage parameters are entered to represent the exfiltration into the surrounding soil.

The soil inputs are all derived from the SWCC of the bioretention media and K_{sat} of each layer. Both of these soil properties require difficult, time-consuming laboratory procedures and have large variability associated with their measurement (Bagarello et al., 2004; Asleson et al, 2009; Pedescoll et al., 2011). DRAINMOD-Urban could benefit from the use of PTFs for developing the SWCC and K_{sat} input parameters as long as model performance is not negatively affected. The SWCC is manually entered into DRAINMOD which then uses a soil preperation program to internally process the remaining soil parameters such as volume drained, upward flux, and Green and Ampt infiltration parameters over varying internal water levels.

The water level versus volume drained is important to account for soil moisture in the bioretention cell as the internal water level fluctuates. The upward flux is the capillary movement at various water table depths. This is used when water is pulled into the root zone to meet ET demand. The upward flux is calculated in the soil preparation program using the Millington and Quirk procedure which estimates the unsaturated hydraulic conductivity from the SWCC and saturated vertical conductivity. The Green-Ampt parameters derived from the SWCC and K_{sat} for each soil layer in the model are used to find an effective K_{sat} based on the internal water level in the bioretention cell. These soil routines imply that a change in the SWCC could substantially affect other calculations in the model and, consequently, the model outputs.

A surface water balance is used to determine overflow based on the depth of ponding. Surface infiltration into the cell and through soil layers is calculated using the Green and Ampt (1911) equation. The outflow from the underdrain pipe was calculated using the the Hooghoudt equation (van Schilfgaarde, 1974) during unsaturated conditions. When the soil profile is saturated, the Kirkham equation is used to calculate subsurface drainage and Darcy’s law is used for vertical seepage into the underlying soil. Saturated and unsaturated conditions were determined by a water balance through the bioretention cell that identified an average water level in the cell.

DRAINMOD-Urban outputs time series of volumes for each component of the water balance including inflow, infiltration, ET, drainage, overflow, water table depth and seepage. The small temporal scale of DRAINMOD-Urban allows for development of hydrographs to analyze peak flows, timing, and hydrologic behavior throughout a storm event. These outputs are beneficial to understanding the dynamics of each hydrologic pathway within a bioretention cell.

4.3.5 DRAINMOD-Urban Calibration Procedures

The UC cell was previously calibrated in DRAINMOD-Urban and model outputs were compared to measured drainage and overflow hydrographs (Lisenbee et al., 2020; Ch. 2). The calibration parameters were the K_{sat} of the bioretention media, K_{sat} of the sand layer (below the bioretention media), the drainage coefficient, and the seepage parameters (piezometric head and thickness of the restricting layer). These parameters were systematically adjusted, and the cumulative NSE and PBIAS (i.e. across all events) were optimized to find the best match between measured and simulated drainage and overflow hydrographs. Drainage and overflow hydrographs were also visually inspected to ensure the calibration statistics reflected the output hydrographs. Hydrographs were also quantified using the volume, peak flow, time to peak and duration of each event. Following calibration, additional statistics (r, R^2, index of agreement (d), relative error counterparts (d_1 and NSE_1), MAE, MSE, RMSE, RSR) were used to confirm the performance of the simulation. For additional information on DRAINMOD-Urban calibration, see Chapter 2.

4.3.6 DRAINMOD-Urban modeling with PTFs

Once the new SWCCs were calculated from the two chosen PTFs, the soil preparation program in DRAINMOD-Urban was used to calculate the Green-Ampt parameters, the upward flux, and volume drained at various internal water levels. These new soil files replaced the original soil file in DRAINMOD-Urban, but all other inputs remained the same as the calibrated model. The saturated hydraulic conductivity of the bioretention media and the sand layer below the bioretention media were also adjusted to represent the calibrated K_{sat} (per Lisenbee et al. 2020), measured K_{sat}, and the K_{sat} calculated in ROSETTA (Table 4.2). Under the measured scenario, the bioretention media is measured as described above but the sand layer was estimated based on previous studies (Winston, 2015; Lisenbee et al., 2020). Because K_{sat} is used as a calibration parameter, it was adjusted beyond the measured or estimated K_{sat} by Lisenbee et al. (2020), resulting in the calibrated

K_{sat}. The K_{sat} calculated with the ROSETTA SSC PTF used the soil texture listed in Table 4.1 for the bioretention media and 100% sand for the sand layer.

Table 4.2 Values of saturated hydraulic conductivity used for the bioretention media and sand layer in the UC cell under measured, calibrated, and ROSETTA PTF K_{sat} scenarios.

Saturated Hydraulic Conductivity (K_{sat}) in cm/hr	Bioretention Media Layer	Sand Layer
Measured*	16.8	30
Calibrated	35	45
ROSETTA PTF	6.7	60

The measured K_{sat} was also compared to the K_{sat} estimated by ROSETTA to create a total of nine scenarios for model comparison (Table 4.3). The event drainage and overflow hydrographs from each of these simulations were compared to measured hydrographs. The NSE and PBIAS were calculated as a cumulative total for each simulation similar to the DRAINMOD-Urban calibration procedure described above. This provided a means of comparison for performance of the calibrated model using measured soil data and PTFs. To address the variability of the measured SWCC, the SWCC measured from each of the triplicate bioretention media soil samples were entered into the calibrated DRAINMOD-Urban and the NSE and PBIAS were calculated for each simulation. This created a range of model performance to compare to the averaged SWCC used in the original calibration.

4.4 RESULTS

4.4.1 Soil Water Characteristic Curves

Various iterations of the ROSETTA PTF noted above (TXT, SSC, SSCBD, and SSCBDθ_{33}) and the Vereecken PTF were used for comparison against the laboratory measured SWCC. The SWCC calculated from the Vereecken PTF most closely matched the measured SWCC at matric potentials greater than 10 kPa (100 cm; Figure 4.2). The field capacity of soil, or the soil moisture at which the soil is no longer free draining, is typically estimated at 33 kPa (330 cm). However, for the coarse-textured soils in this study, the field capacity was estimated at 10 kPa (100 cm). Since our study has a large focus on drainage through a bioretention cell, the moisture content at field capacity could impact the performance of DRAINMOD-Urban by indicating when drainage from the bioretention media has stopped. The ROSETTA SWCC estimates were closer to the measured SWCC in the region less than 10 kPa (100 cm) matric potential, with the simulation using only the percent sand, silt, and clay (SSC) being the closest to measured at saturation.

The soil porosity (i.e. soil moisture at zero matric potential) varies across the measured, Vereecken, and ROSETTA PTFs although all ROSETTA iterations are similar. The Vereecken PTF seems to underestimate the porosity or saturated moisture content at 0.239 cm^3/cm^3, but the ROSETTA SSC PTF overestimates the saturated moisture content at 0.373 cm^3/cm^3 (compared to a measured porosity of 0.331 cm^3/cm^3). Because the ROSETTA SSC PTF resulted in the SWCC closet to the measured SWCC from all the ROSETTA PTFs, it was the only ROSETTA PTF utilized in subsequent modeling. Using SWCCs from two PTFs that best match the measured SWCC at opposite matric potentials, creates an experimental setup to infer which matric potentials along the SWCC are most sensitive in DRAINMOD-Urban simulations.

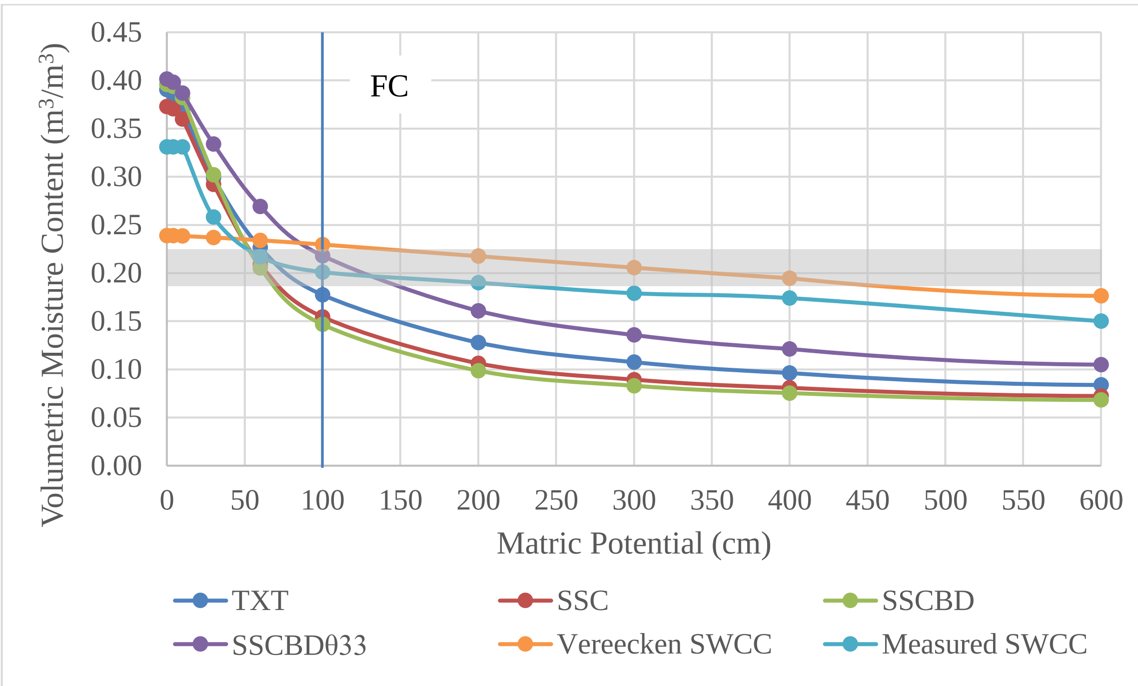


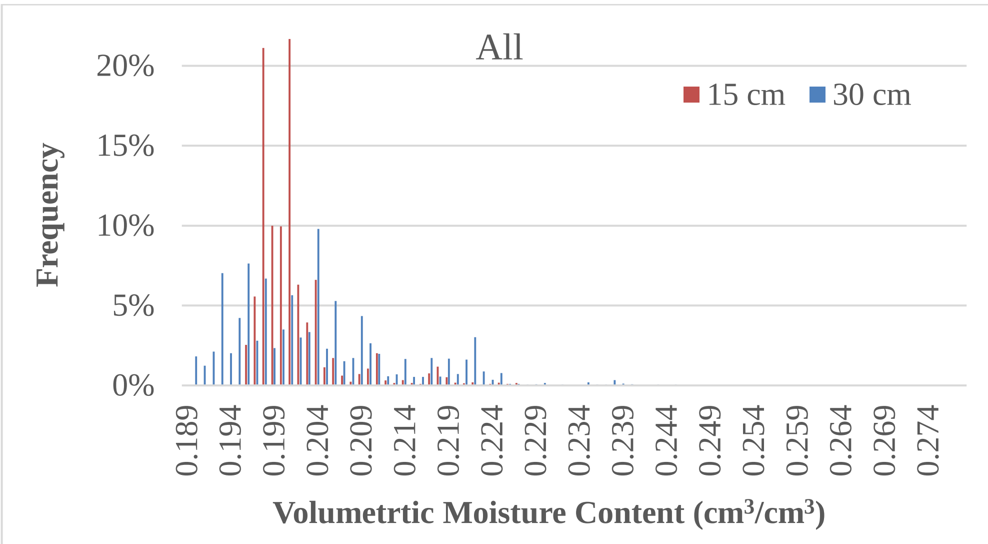
Figure 4.2 Comparison of measured soil water characteristic curve (SWCC) compared to the SWCC derived from the Vereecken pedotransfer function (PTF) and various ROSETTA PTFs using only soil texture (TXT), percent sand, silt, and clay (SSC), percent sand, silt, and clay and bulk density (SSCBD), and percent sand, silt, and clay, bulk density, and moisture content at field capacity (SSCBDθ33). Field capacity (FC) at 10 kPa matric potential is denoted by a vertical line. The greyed area indicates 98% of measured moisture content.

4.4.2 Soil Moisture

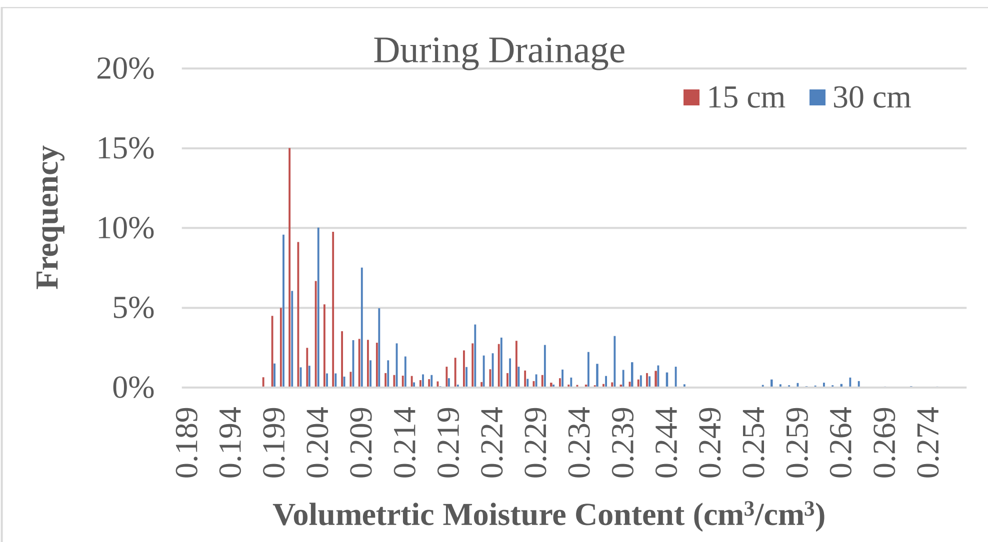
After examining differences in the SWCC, measured soil moisture data was evaluated to determine what range of moisture content the UC bioretention cell operated at most often (Figure 4.3). It was determined that 98% of the measured moisture content in the bioretention media fell within an operating range of 0.189-0.225 cm^3/cm^3 (Figure 4.2 & 4.3a). This includes interevent periods when drainage has ceased and the bioretention media becomes drier through ET. However, the lowest measured soil moisture at 0.189 cm^3/cm^3 is not much smaller than field capacity estimated at 0.201 cm^3/cm^3. The moisture content of the bioretention media during measured drainage events was a higher range, 0.198-0.313 cm^3/cm^3, with 30% and 44% of measurements (from 15 cm and 30 cm below the bioretetnion media, respectively) in the range ±1.5% of the field capacity (0.198-0.204 cm^3/cm^3; Figure 4.3b). This shows that soil mositure remains near field capacity for much of the drainage event. Additionally, the maximum measured moisture content in the bioretention media was 0.312 cm^3/cm^3 and in the IWS and storage layer was 0.354 cm^3/cm^3.

The most critical consideration when evaluating the SWCC is the range of soil moisture conditions actually experienced by the bioretention cell during operation. The field capacity taken at 10 kPa from the measured SWCC (0.201 cm^3/cm^3) falls within the measured operating range of soil moisture. The SWCC from the Vereecken PTF has a field capacity of 0.230 cm^3/cm^3 at 10 kPa which is slightly higher than the measured operating range for soil moisture. The ROSETTA PTFs are more similar to the measured SWCC near saturation, but the measured data indicates that the bioretention media is never fully saturated (Figure 4.3). The maximum measured moisture content in the bioretention media is higher than the saturation point for the SWCC from the Vereecken PTF. However, when these SWCC predictions are entered into DRAINMOD-Urban, the model may make assumptions in model processes that lead to more sensitivity at certain parts of the SWCC.

Therefore, the best match to the measured SWCC in the soil moisture operating range may not be reflected in model outcomes.



a)



b)

Figure 4.3 Histograms of measured soil moisture (cm^3/cm^3) at 15 cm and 30 cm below the soil surface for all soil moisture measurements (a) and those that occurred during drainage events (b). The bioretention media in the Ursuline Cell extends from 0 to 60 cm below the soil surface, with the internal water storage layer at 45-105 cm below the soil surface.

4.4.3 Saturated Hydraulic Conductivity (K_{sat})

As noted above, K_{sat} for this study took on three forms: laboratory measured, calibrated in previous DRAINMOD-Urban modeling, and predicted via the ROSETTA PTF (Table 4.2). The bioretention layer and sand layer were calibrated together by Lisenbee et al., (2020) and so they were both evaluated for each K_{sat} scenario in this study. The measured K_{sat} of the bioretention media was paired with an estimated K_{sat} for the sand layer as that was the procedure done in previous modeling studies (Winston, 2015). The K_{sat} estimated by ROSETTA for the bioretention media and the sand layer are very different given that the bioretention media is 87% sand (compared to 100% sand; Table 4.2). This indicates large variability of K_{sat}, even across similar soil textures. There is also a wider range in the ROSETTA predicted K_{sat} for the sand and bioretention media (a difference of 53 cm/hr) compared to the calibrated K_{sat} that performed best when closer to each other (a difference of 10 cm/hr) and the measured scenario with a difference of 13 cm/hr. Since these values were changed together, their influence on model outcomes is combined. It would be interesting to consider the sensitivity of each of these parameters in the model individually and then compare the influence of calibrtion, laboratory measurement, and PTFs. Additionally, this study only considered the ROSETTA PTF but other PTFs are available to calcualte K_{sat} which could be considered in future studies.

4.4.4 DRAINMOD-Urban Performance

<u>4.4.4.1 Comparison of Soil Water Characteristic Curves in DRAINMOD-Urban</u>

The drainage and overflow hydrographs produced by DRAINMOD-Urban using each PTF were compared to measured hydrographs (Figures 4.5 & 4.6) and the NSE and

PBIAS were used to compare cumulative model performance (Table 4.3). An NSE>0.4 is acceptable model performance at a daily timestep (Skaggs et al., 2012). As model performance is compared among different SWCC and K_{sat} scenarios, it is important to note that, even at a much smaller 2-minute timestep, all scenarios provided acceptable model performance for drainage hydrographs.

With a calibrated K_{sat}, the SWCC from the ROSETTA PTF achieved a similar NSE for both drainage (0.59) and overflow (-0.06) hydrographs in DRAINMOD-Urban compared to the measured SWCC (Table 4.3). The PBIAS was larger with the ROSETTA-derived SWCC for drainage hydrographs but smaller in overflow hydrographs. The Vereecken PTF had the worst performance of drainage and overflow hydrographs in DRAINMOD-Urban based on both NSE and PBIAS for the calibrated K_{sat} simulations (Table 4.3).

In the case that the measured SWCC and K_{sat} were used without calibration in DRAINMOD-Urban (but other calibration parameters were held constant), the performance of drainage and overflow hydrographs was reduced compared to calibration (Table 4.3). Under the measured K_{sat} condition, the Vereecken PTF performed similarly to the measured SWCC for drainage hydrographs and achieved the same NSE and PBIAS for overflow hydrographs. Meanwhile, ROSETTA had the worst performance for drainage hydrographs and the best performance for overflow hydrographs based on NSE and PBIAS.

Next, K_{sat} was adjusted to the values suggested by the ROSETTA PTF based on soil texture. These values were used in DRAINMOD-Urban with each SWCC scenario (measured, Vereecken PTF, and ROSETTA PTF) and there was minimal change in the performance across simulations although the ROSETTA PTF performed best on drainage and overflow (Table 4.3).

Table 4.3 Comparison of DRAINMOD-Urban performance under measured, Vereecken PTF, and ROSETTA PTF SWCC and K_{sat} that was measured, calibrated and calculated with the ROSETTA PTF.

		Measured SWCC		Vereecken PTF		ROSETTA PTF	
		Drainage	**Overflow**	**Drainage**	**Overflow**	**Drainage**	**Overflow**
Calibrated K_{sat}	**NSE**	0.60	-0.10	0.48	-0.22	0.59	-0.06
	PBIAS	5.19	-18.47	16.44	-19.27	22.48	3.46
Measured K_{sat}	**NSE**	0.52	-0.71	0.49	-0.71	0.45	-0.34
	PBIAS	18.79	-37.66	18.75	-38.15	31.37	-15.01
ROSETTA K_{sat}	**NSE**	0.46	-0.62	0.44	-0.63	0.49	-0.36
	PBIAS	22.58	-33.65	26.07	-34.12	27.57	-7.74

To understand how the variability of the measured SWCC adds uncertainty to these results, the SWCC measured from each of the three bioretention media soil samples taken from the UC cell were input to a calibrated DRAINMOD-Urban model (Figure 4.4). The range of performance for drainage and overflow hydrographs for each individual SWCC was compared to the average which was used in the DRAINMOD-Urban calibration (Table 4.4). The NSE ranged from 0.53 to 0.64 and the PBIAS from 17.7 to 27.9 for drainage hydrographs. For overflow hydrographs, the range spanned a slightly smaller range from -0.14 to -0.08 for the NSE and -9.5 to -1.5 for the PBIAS. These results indicated that DRAINMOD-Urban is not particularly senstitive to changes in the SWCC. For the DRAINMOD-Urban simulations using the calibrated K_{sat}, the ROSETTA PTF fell within the same performance ranges as that of the three measured SWCCs. This indicates that the ROSETTA PTF may be a viable option in place of laboratory tests to determine the SWCC for DRAINMOD-Urban. This could significantly decrease the time, effort, and data required to achieve the same results in calibrated simulations.

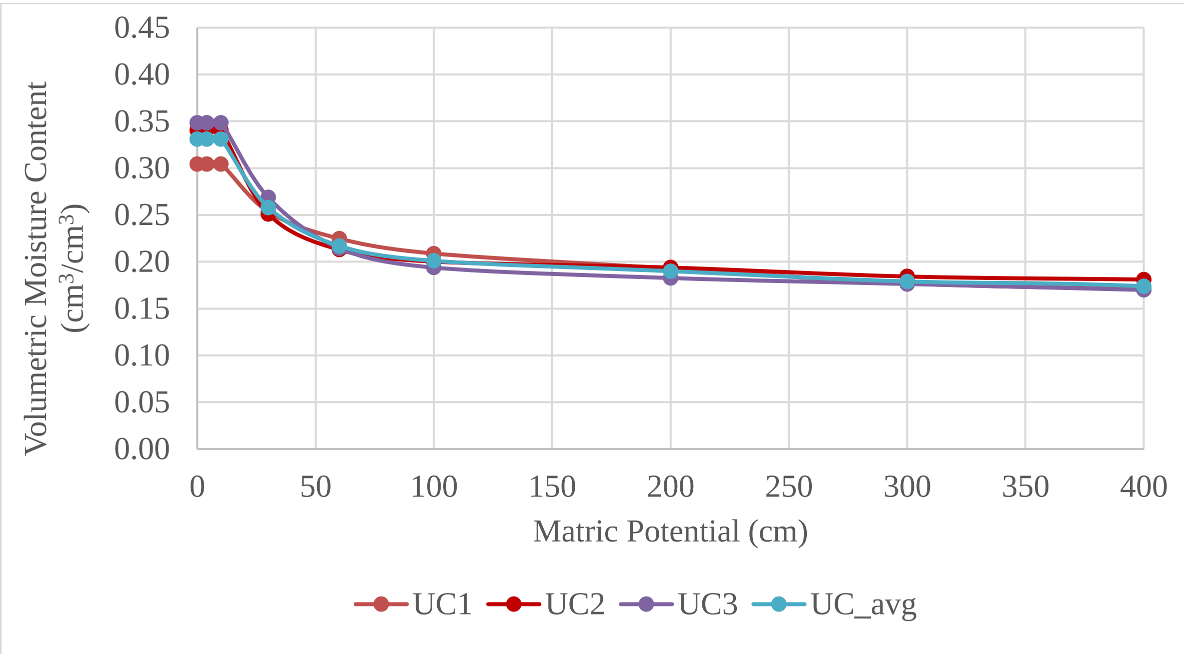


Figure 4.4 Measured soil-water characteristic curve (SWCC) from each of the individual samples tested in the laboratory compared to the average measured SWCC (used in previous DRAINMOD-Urban modeling).

Table 4.4 Goodness-of-fit tests to describe the performance of DRAINMOD-Urban when using the measured soil-water characteristic curve (SWCC) from each of the individual samples tested in the laboratory compared to the performance of DRAINMOD-Urban using the average measured SWCC.

	DRAINAGE		OVERFLOW	
Measured SWCC	**NSE**	**PBIAS**	**NSE**	**PBIAS**
Average	**0.60**	**5.19**	**-0.10**	**-18.47**
Sample 1	0.64	17.7	-0.14	-9.5
Sample 2	0.53	27.9	-0.08	-2.2
Sample 3	0.61	19.0	-0.08	-1.5

4.4.4.2 Comparison of K_{sat} in DRAINMOD-Urban

The significance of the bioretention media and sand layer K_{sat} on the performance of DRAINMOD-Urban can be described when the SWCC was held constant and the K_{sat} was changed from calibrated to measured to calculated by ROSETTA. For all simulations with the measured SWCC, the change in K_{sat} had a large impact on the NSE ranging from 0.60 to 0.46 for drainage hydrographs and -0.71 to -0.10 for overflow hydrographs. The PBIAS also increased for drainage and overflow as K_{sat} was changed from calibrated to measured to ROSETTA-estimated values.

Using the Vereecken PTF to calculate the SWCC, the drainage performance of DRAINMOD-Urban changed very little with K_{sat} compared to other SWCC scenarios. The drainage NSE ranged from 0.44 to 0.49 and the overflow NSE ranged from -0.71 to -0.22. This could be related to the small change in moisture content of the Vereecken SWCC at matric potentials below 10 kPa, where the bioretention cell tends to operate. Finally, with the ROSETTA-derived SWCC, the calibrated K_{sat} performed best, but the ROSETTA K_{sat}

had a higher drainage NSE (and similar overflow NSE) than the measured K_{sat} despite seemingly large differences in the measured and ROSETTA K_{sat} for the bioretention media and sand layer. This indicates that the measured K_{sat} may not be necessary when using a PTF in lieu of a measured SWCC because the model performs best when K_{sat} is calibrated. However, if calibration is not possible, the ROSETTA PTF will provide an estimated K_{sat} that will perform similarly to the measured K_{sat}. Although overflow performance was poor for all scenarios, the SWCC from the ROSETTA PTF produced the best performance of overflow hydrographs across all K_{sat} scenarios.

4.4.4.3 Hydrographs

The effect on the individual drainage and overflow hydrographs was qualitatively examined in addition to the quantitative cumulative performance. One of the events with the best drainage calibration was chosen to evaluate and compare the hydrographs for each of the scenarios in Table 4.3 (Figure 4.5). Although the hydrographs under all scenarios visually appeared almost identical, when examined closely some small changes are identified (Figure 4.5). For all forms of SWCCs, the scenarios with the calibrated K_{sat} showed better timing of the falling limb and better capture of the peak flow on the second peak (Figure 4.5). For all nine scenarios, this example event has a plateau that appears on the first peak of DRAINMOD-Urban hydrographs, but the height of the plateau depends on the K_{sat} of the bioretention media and sand layers (Figure 4.5). This suggests that the K_{sat} could be a limiting factor in some cases. Also, the K_{sat} may be more sensitive to the hydrographs produced by the model than the SWCC. More sensitivity analysis on DRAINMOD-Urban's response to changes in the K_{sat} and SWCC parameters is recommended.

The overflow hydrographs showed no visible change between the measured and Vereecken PTF scenarios which is supported by the cumulative results in Table 4.3 (Figure 4.6). The ROSETTA PTF showed a slight decrease in the first peak (causing it to be closer to the measured peak) compared to the measured and Vereecken PTF in all K_{sat} conditions (Figure 4.6). For the K_{sat} variations, the calibrated K_{sat} produced overflow peaks closest to measured peaks (Figure 4.6).

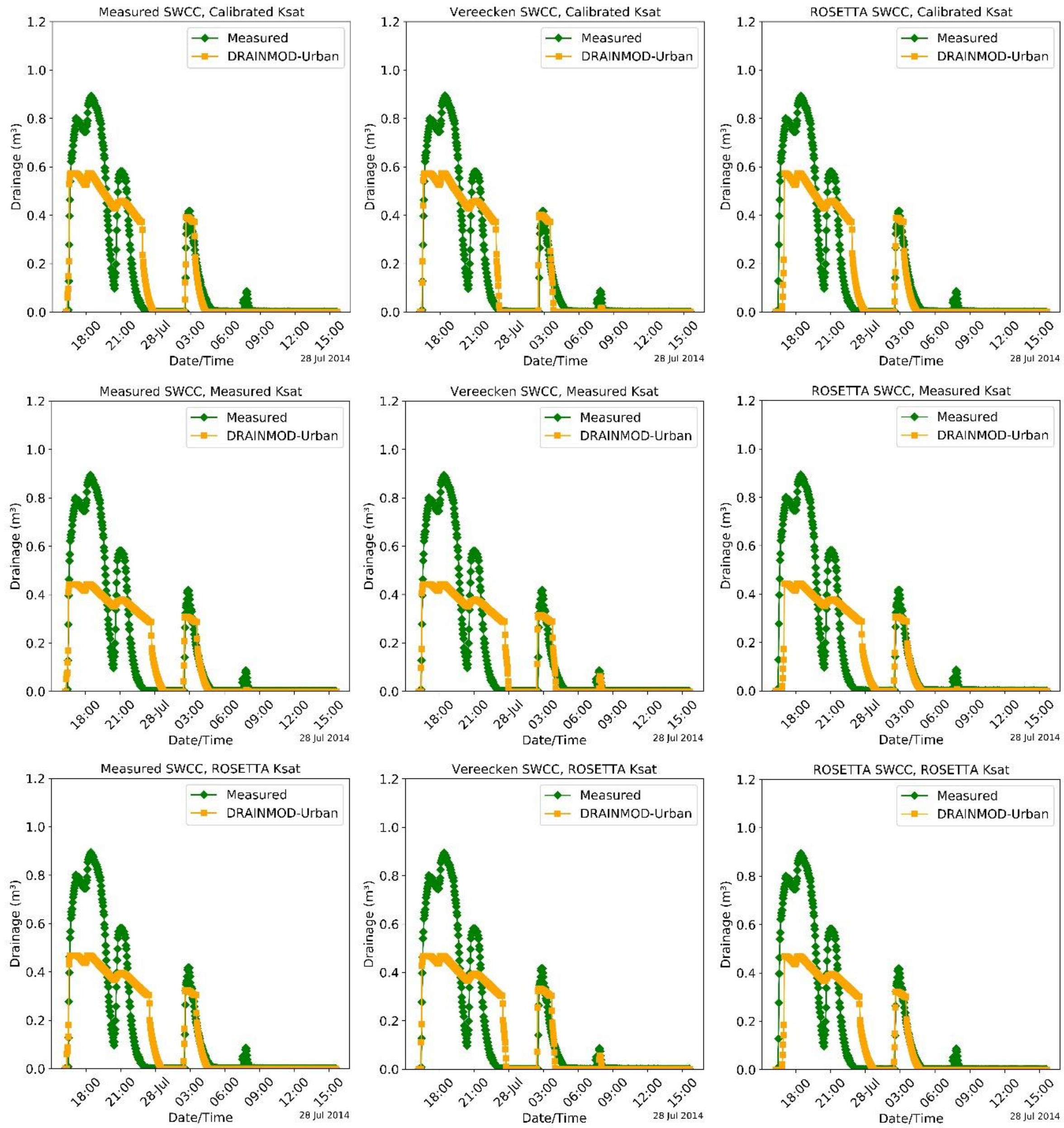


Figure 4.5. Example of modeled and measured drainage hydrographs from DRAINMOD-Urban using three water retention curves (measured, Vereecken PTF and ROSETTA PTF) and three Ksat values (calibrated, measured and ROSETTA PTF).

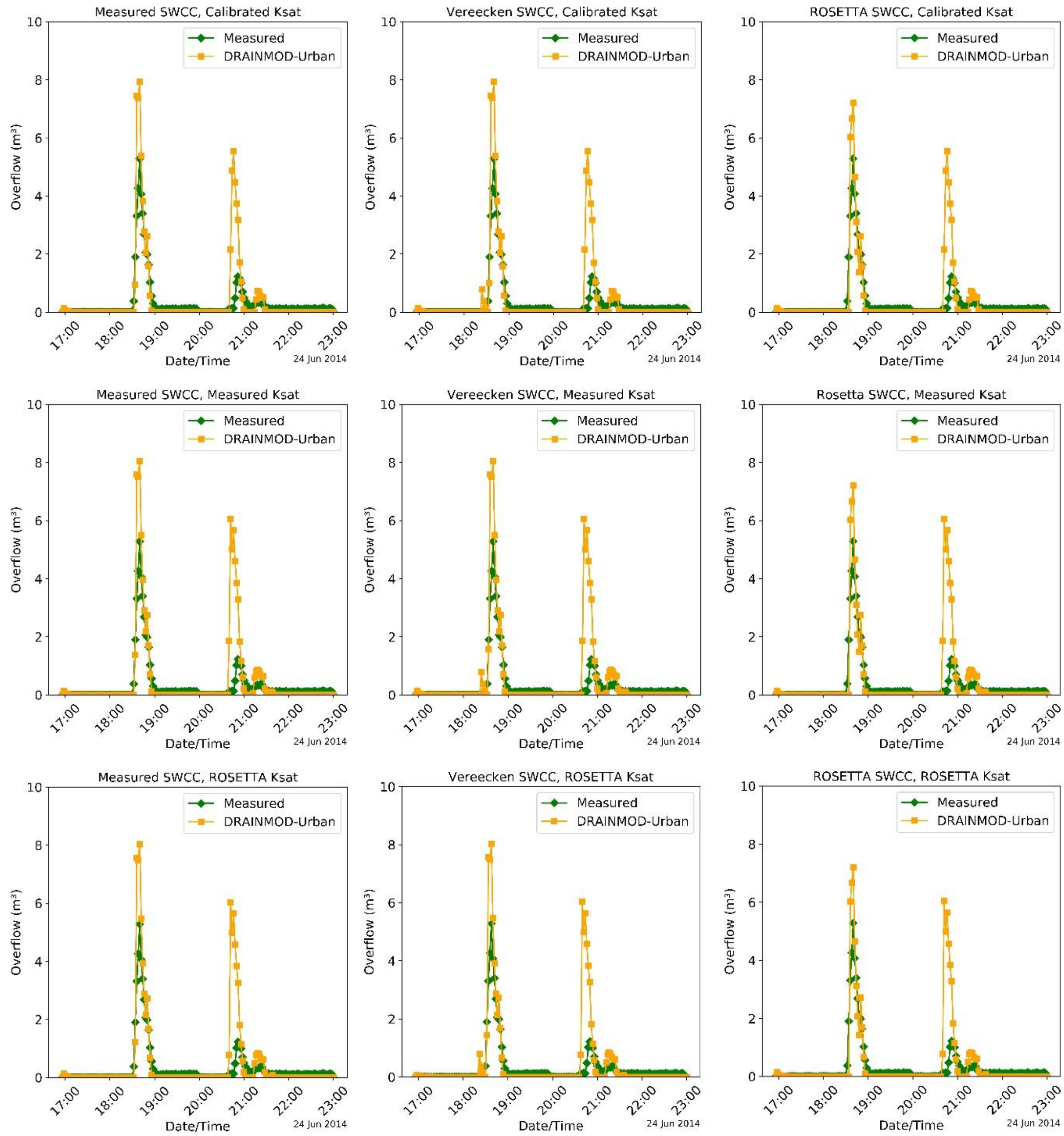


Figure 4.6. Example of modeled and measured overflow hydrographs from DRAINMOD-Urban using three water retention curves (measured, Vereecken PTF and ROSETTA PTF) and three Ksat values (calibrated, measured and ROSETTA PTF).

4.4.4.3 Volumes

The drainage and overflow volumes output from DRAINMOD-Urban for each event were evaluated for SWCC and K_{sat} scenarios. For the calibrated K_{sat}, the measured SWCC performed best for drainage reaching an NSE=0.83 compared to NSE=0.69 for the Vereecken PTF and NSE=0.73 for ROSETTA PTFs (Table 4.5). The overflow event volumes from the ROSETTA PTF performed almost as well as the measured SWCC with NSE=0.68 and 0.66, respectively. Additionally, the ROSETTA PTF produced total overflow only 4 m^3 less than the total measured overflow volume. The Vereecken PTF NSE was 0.48 and overestimated total overflow volumes by 26 m^3 (Table 4.5).

For scenarios using the measured K_{sat}, a decrease in NSE was noted for all SWCCs compared to the calibrated K_{sat}, especially for overflow. The ROSETTA-derived SWCC performed best (even better than the measured SWCC) for both drainage and overflow volumes (Table 4.5). Finally, for scenarios using the ROSETTA K_{sat}, the ROSETTA-derived SWCC performed slightly better than the measured SWCC for the drainage volumes (NSE=0.64 and NSE=0.61, respectively) but performed much better for overflow volumes (NSE=0.50 and NSE=0.05, respectively).

When evaluating the results based on PBIAS, all SWCCs overestimated volumes similarly between 24 to 39 percent for drainage and 23 to 41 percent for overflow (Table 4.5). The exception was the drainage and overflow of the scenario utilizing measured SWCC and calibrated K_{sat}. The overflow had larger PBIAS than other overflow volumes at 67 percent. The drainage in this simulation had the only negative PBIAS, suggesting an average underestimation of simulated values across event volumes (Table 4.5). This simulation was also the only simulation with total drainage volume greater than measured.

Modeled event volumes compared to measured drainage and overflow volumes can be visualized in Figure 4.7. As expected, based on the volumes in Table 4.5, the event volumes are very similar among SWCC types for both the measured and ROSETTA K_{sat}. For these simulations, the events with the largest volumes show the most discrepancy between measured and simulated values, and the most variability among SWCC types. In particular, under the calibrated K_{sat}, there was more variation in the volumes predicted between each SWCC. The measured SWCC scenarios seemed to primarily result in overestimated drainage volumes and the Vereecken and ROSETTA PTF-derived SWCC scenarios produced volumes much closer to the 1:1 line except for the largest measured drainage volume (Figure 4.7). The calibrated K_{sat} showed larger discrepancy among SWCCs as overflow event volumes increased (Figure 4.7). This could indicate that the K_{sat} has a larger influence on drainage and overflow volumes than the SWCC, but more sensitivity analysis across multiple bioretention cells is required to validate this conjecture.

4.4.4.4 DRAINMOD-Urban Performance Summary

All performance statistics for drainage hydrographs showed good performance considering NSE was taken at 2-min timesteps across hydrographs. The hydrographs themselves seemed to respond less to changes in SWCC than changes in K_{sat}, i.e. K_{sat} affected drainage and overflow peak flow more than SWCC. Across all scenarios, the calibrated K_{sat} and measured SWCC provided the best model performance of drainage and overflow hydrographs (in NSE and PBIAS) but the calibrated K_{sat} and ROSETTA PTF-derived SWCC was a close second in drainage with slightly better overflow results. The same trend was true for the drainage and overflow event volumes which validates that there was no discrepancy between the hydrograph and volume results.

Table 4.5. Comparison of total drainage and overflow volumes for DRAINMOD-Urban simulations with a calibrated K_{sat} and measured, Vereecken PTF, and ROSETTA PTF SWCC.

		Measured Vol.		Measured SWCC		Vereecken PTF		ROSETTA PTF	
		Drainage (m^3)	Overflow (m^3)	Drainage (m^3)	Overflow (m^3)	Drainage (m^3)	Overflow (m^3)	Drainage (m^3)	Overflow (m^3)
Calibrated K_{sat}	TOTAL	693	131	871	102	561	157	531	127
	NSE			0.83	0.66	0.69	0.48	0.73	0.68
	PBIAS			-47	67	30	28	24	27
Measured K_{sat}	TOTAL	693	131	563	181	543	182	470	151
	NSE			0.51	-0.10	0.53	-0.16	0.62	0.45
	PBIAS			34	41	31	40	32	23
ROSETTA K_{sat}	TOTAL	693	131	537	176	513	176	482	142
	NSE			0.61	0.05	0.46	0.001	0.64	0.50
	PBIAS			36	38	39	38	31	27

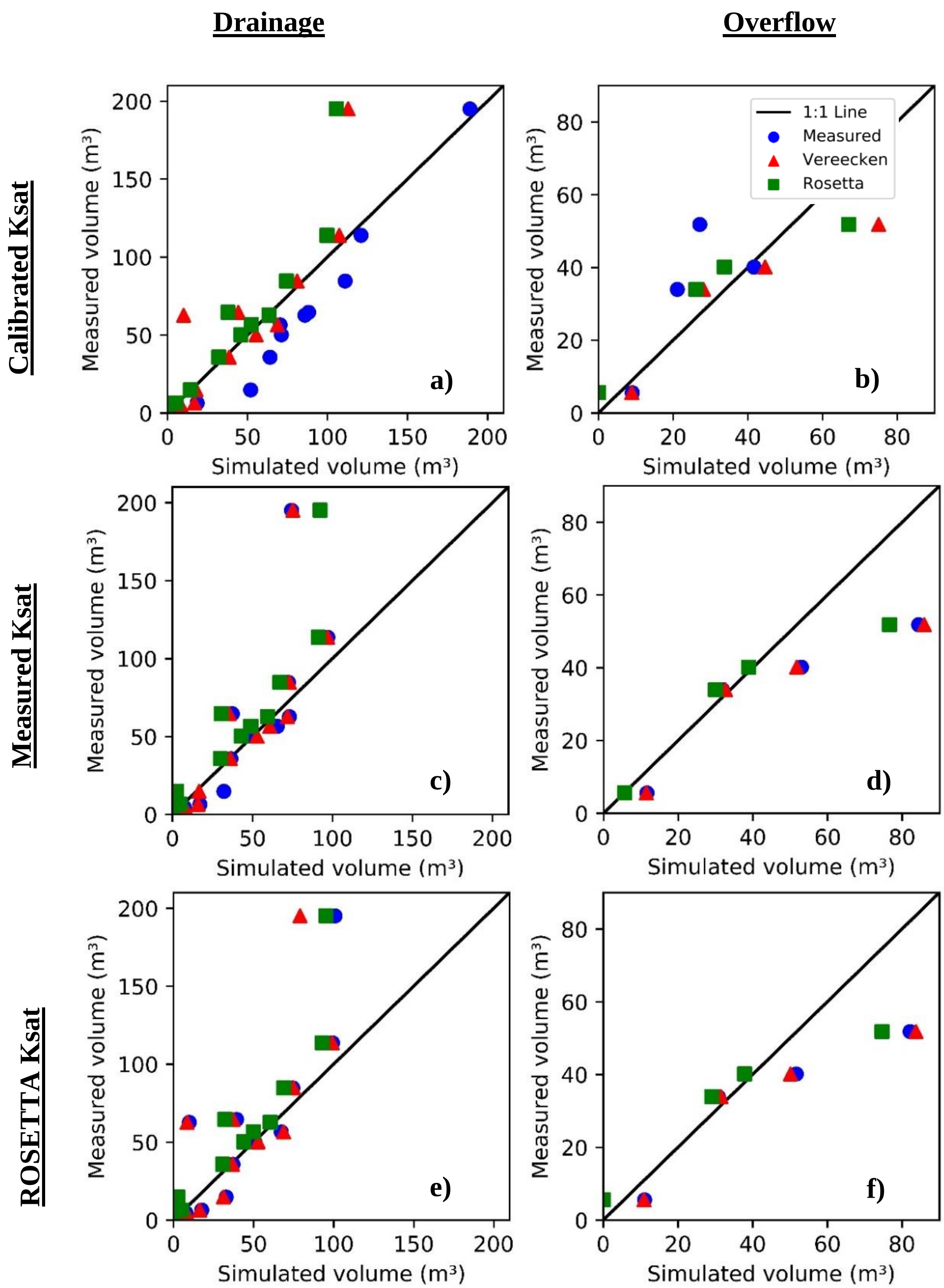


Figure 4.7. Modeled and measured drainage and overflow volumes from DRAINMOD-Urban using three different SWCC (measured (circle), Vereecken PTF (triangle) and ROSETTA PTF (square)) under three variations of K_{sat}: calibrated, measured and ROSETTA PTF.

4.5 Conclusions

This study showed that a calibrated DRAINMOD-Urban model can perform equally well with a SWCC that is measured to one that is calculated using the ROSETTA PTF. This is a significant discovery because it may eliminate the need for time-consuming soil measurements when using sandy bioretention media. Despite the Vereecken PTF creating an SWCC more similar to the measured SWCC near field capacity, the model performance declined compared to other SWCC simulations. This could mean that even though the measured soil moisture is often near field capacity, the soil moisture at lower matric potentials is more sensitive in DRAINMOD-Urban.

K_{sat} was also investigated for calibrated, measured, and ROSETTA values to determine if K_{sat} measurement was necessary for predicting bioretention cell processes with DRAINMOD-Urban. The calibrated K_{sat} performed best but the measured and ROSETTA K_{sat} performed similarly in DRAINMOD-Urban. Therefore, if calibration is not possible, using ROSETTA to estimate K_{sat} could be substituted for measuring K_{sat}, especially if the SWCC is also estimated with a PTF.

The K_{sat} scenarios in this study represented the range of decisions made by modelers. Does the model require calibration of K_{sat}? If K_{sat} needs to be calibrated anyway, then why measure it? But if calibration is not possible, do measured values provide better model performance than estimations to justify time and effort spent on soil testing? While this study touches on each of these questions with the K_{sat} from ROSETTA PTF, further investigation is warranted.

This study began with a model calibrated in a previous study (Lisenbee et al., 2020), but modelers do not always have field data for model calibration. Therefore, many more questions can be investigated regarding the effect of calibration. How would the scenarios presented in this study be different if calibration was not possible and all calibration parameters were simply estimated? How does the sensitivity of the other calibration parameters in DRAINMOD-Urban (drainage coefficient, piezometric head, and thickness of the restricting layer) affect the level of accuracy required of the PTF-derived soil parameters? The sensitivity of the SWCC and K_{sat} in DRAINMOD-Urban is also important because the interactions between the SWCC and K_{sat} affect model performance. Understanding whether the SWCC or K_{sat} is more sensitive in DRAINMOD-Urban will help users choose where to invest in measured soil parameters or PTFs.

Lastly, more studies are needed that investigate additional PTFs, field study sites, and bioretention models. Studies considering other PTFs for K_{sat} and SWCC prediction should be considered in future bioretention modeling studies. Investigating multiple PTFs for bioretention media soil properties could identify other PTFs that are well-suited for coarse-textured bioretention media. Alternatively, a PTF could be developed from a database of bioretention media soil characteristics. Additionally, more study sites with monitored bioretention cells need to be investigated to validate findings from this study and to find patterns in bioretention media and how it is represented in bioretention models. For instance, overflow in this study generally performed poorly based on only four monitored overflow events. Studies with more frequent overflow are necessary to confirm patterns found in DRAINMOD-Urban performance of overflow. Furthermore, this study only considers the use of PTFs in one model, but a variety of soil parameters are required for different bioretention models. Models with more complex or more simple soil inputs would respond differently to substituting PTFs for typically measured soil properties.

4.6 References

Akan, A.O. (2013) Preliminary Design Aid for Bioretention Filters. Journal of Hydrologic Engineering 18(3), 318-323. https://doi.org/10.1061/(Asce)He.1943-5584.0000554
ASTM (2007) Standard Test Method for Particle-Size Analysis of Soils (Astm D422-63).
ASTM (2014) Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils (Astmd2974-14).
ASTM (2018) Standard Test Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens (Astm D7263-09(2018)E2), ASTM International, West Conshohocken, PA.
Barbu, I.A. and Ballestero, T.P. (2015) Unsaturated Flow Functions for Filter Media Used in Low-Impact Development—Stormwater Management Systems. Journal of Irrigation and Drainage Engineering 141(1), 04014041. https://doi.org/10.1061/(asce)ir.1943-4774.0000766
Brown, R.A., Skaggs, R.W. and Hunt, W.F. (2013) Calibration and Validation of DRAINMOD to Model Bioretention Hydrology. Journal of Hydrology 486, 430-442. https://doi.org/10.1016/j.jhydrol.2013.02.017
Carsel, R.F. and Parrish, R.S. (1988) Developing Joint Probability-Distributions of Soil-Water Retention Characteristics. Water Resources Research 24(5), 755-769. https://doi.org/DOI 10.1029/WR024i005p00755
Garcia-Gutierrez, C., Pachepsky, Y. and Martin, M.A. (2018) Technical Note: Saturated Hydraulic Conductivity and Textural Heterogeneity of Soils. Hydrology and Earth System Sciences 22(7), 3923-3932. https://doi.org/10.5194/hess-22-3923-2018
Gwenzi, W., Hinz, C., Holmes, K., Phillips, I.R. and Mullins, I.J. (2011) Field-Scale Spatial Variability of Saturated Hydraulic Conductivity on a Recently Constructed Artificial Ecosystem. Geoderma 166(1), 43-56. https://doi.org/10.1016/j.geoderma.2011.06.010
Hathaway, J.M., Brown, R.A., Fu, J.S. and Hunt, W.F. (2014) Bioretention Function under Climate Change Scenarios in North Carolina, USA. Journal of Hydrology 519, 503-511. https://doi.org/10.1016/j.jhydrol.2014.07.037
Kirkham, M.B. (2005) Principles of Soil and Plant Water Relations. Kirkham, M.B. (ed), pp. 101-115, Academic Press, Burlington.
Klute, A. (1986) Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods. Klute, A. (ed), pp. 635–662, Soil Science Society of America, Madison, WI.
Liao, K.H., Xu, S.H., Wu, J.C., Ji, S.H. and Lin, Q. (2011) Assessing Soil Water Retention Characteristics and Their Spatial Variability Using Pedotransfer Functions. Pedosphere 21(4), 413-422. https://doi.org/Doi 10.1016/S1002-0160(11)60143-4
Mualem, Y. (1977) Extension of Similarity Hypothesis Used for Modeling Soil-Water Characteristics. Water Resources Research 13(4), 773-780. https://doi.org/DOI 10.1029/WR013i004p00773
Nemes, A., Pachepsky, Y. and Timlin, D. (2011) Toward Improving Global Estimates of Field Soil Water Capacity. Soil Sci. Soc. Am. J. 75(3), 807-812. https://doi.org/10.2136/sssaj2010.0251
Pachepsky, Y. and Rawls, W.J., (eds) (2004) Development of Pedotransfer Functions in Soil Hydrology, Elsevier Science, Amsterdam.

Papanicolaou, A.N., Elhakeem, M., Wilson, C.G., Burras, C.L., West, L.T., Lin, H., Clark, B. and Oneal, B.E. (2015) Spatial Variability of Saturated Hydraulic Conductivity at the Hillslope Scale: Understanding the Role of Land Management and Erosional Effect. Geoderma 243, 58-68. https://doi.org/10.1016/j.geoderma.2014.12.010

Patil, N.G. and Singh, S.K. (2016) Pedotransfer Functions for Estimating Soil Hydraulic Properties: A Review. Pedosphere 26(4), 417-430. https://doi.org/10.1016/s1002-0160(15)60054-6

Rawls, W.J. and Brakensiek, D.L. (1982) Estimating Soil-Water Retention from Soil Properties. Journal of the Irrigation and Drainage Division-Asce 108(2), 166-171. <Go to ISI>://WOS:A1982NS80900007

Rawls, W.J., Gimenez, D. and Grossman, R. (1998) Use of Soil Texture, Bulk Density, and Slope of the Water Retention Curve to Predict Saturated Hydraulic Conductivity. Transactions of the Asae 41(4), 983-988. <Go to ISI>://WOS:000075662800010

Richards, L.A. and Weaver, L.R. (1944) Moisture Retention by Some Irrigated Soils as Related to Soil Moisture Tension. Journal of Agricultural Research 69, 215-235.

Salazar, O., Wesstrom, I. and Joel, A. (2008) Evaluation of DRAINMOD Using Saturated Hydraulic Conductivity Estimated by a Pedotransfer Function Model. Agricultural Water Management 95(10), 1135-1143. https://doi.org/10.1016/j.agwat.2008.04.011

Saxton, K.E., Rawls, W.J., Romberger, J.S. and Papendick, R.I. (1986) Estimating Generalized Soil-Water Characteristics from Texture. Soil Science Society of America Journal 50(4), 1031-1036. https://doi.org/DOI 10.2136/sssaj1986.03615995005000040039x

Schaap, M.G. and Leij, F.J. (1998) Using Neural Networks to Predict Soil Water Retention and Soil Hydraulic Conductivity. Soil & Tillage Research 47(1-2), 37-42. https://doi.org/Doi 10.1016/S0167-1987(98)00070-1

Schaap, M.G., Leij, F.J. and van Genuchten, M.T. (2001) Rosetta: A Computer Program for Estimating Soil Hydraulic Parameters with Hierarchical Pedotransfer Functions. Journal of Hydrology 251(3-4), 163-176. https://doi.org/Doi 10.1016/S0022-1694(01)00466-8

van Genuchten, M.T. (1980) A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. Soil Science Society of America Journal 44, 892-898.

Warrick, A.W. and Nielsen, D.R. (1980) Applications of Soil Physics. Hill, D. (ed), pp. 319–344, Academic Press, Inc., New York.

Winston, R.J. (2015) Resilience of Green Infrastructure under Extreme Conditions. Doctoral dissertation.

Wosten, J.H.M., Finke, P.A. and Jansen, M.J.W. (1995) Comparison of Class and Continuous Pedotransfer Functions to Generate Soil Hydraulic Characteristics. Geoderma 66(3-4), 227-237. https://doi.org/Doi 10.1016/0016-7061(94)00079-P

Wosten, J.H.M., Pachepsky, Y.A. and Rawls, W.J. (2001) Pedotransfer Functions: Bridging the Gap between Available Basic Soil Data and Missing Soil Hydraulic Characteristics. Journal of Hydrology 251(3-4), 123-150. https://doi.org/Doi 10.1016/S0022-1694(01)00464-4

SUMMARY & CONCLUSION

The four studies in Chapters 1-4 are designed to evaluate a new model for bioretention modeling, DRAINMOD-Urban, through calibration to measured data, comparison to other bioretention models, and examination of input parameters such as soil properties.

Chapter 1 describes the hydrologic and hydraulic processes of DRAINMOD-Urban in comparison to other common bioretention models. The advantages of using DRAINMOD-Urban are that it is a continuous, long-term simulation model that can produce hydrograph outputs at time steps down to 1-minute, and it was designed explicitly for bioretention applications. DRAINMOD-Urban also has the most advanced drainage equations of the models evaluated which includes the ability to model multiple drains and IWS zones. Although DRAINMOD-Urban does not use the most advanced infiltration processes (Richards' equation), it modifies the Green-Ampt equation by incorporating the SWCC to account for changes in soil moisture in the bioretention cell. DRAINMOD-Urban is currently a site-scale model and could be improved by linking its bioretention hydrology with the hydraulics of a catchment-scale model. Other improvements include the ability to account for variability of vegetation process and soil properties over time.

Chapter 2 tested the ability of DRAINMOD-Urban to replicate measured drainage and overflow hydrographs and event volumes through different calibration approaches. DRAINMOD-Urban was able to replicate drainage hydrographs well (NSE=0.60) especially considering the small 2-minute time steps. As expected, the shape of drainage hydrographs predicted by DRAINMOD-Urban was significantly improved after hydrograph calibration. Overflow hydrographs were not as well-represented (NSE=-0.1) which could be due to a combination of a small dataset, bias of the NSE statistic towards peak flow, and model processes. Despite poor statistical performance of overflow events, individual event hydrographs showed excellent timing of flow and overestimated peak flow. More research is required on overflow events to measure the performance of DRAINMOD-Urban for overflow prediction. Both hydrographs and event volumes were improved with hydrograph calibration in DRAINMOD-Urban compared to the volume calibration in the original DRAINMOD. Therefore, this study demonstrated that DRAINMOD-Urban can model bioretention systems at a small temporal scale with good accuracy.

Chapter 3 compared DRAINMOD-Urban to the most widely-used bioretention model in industry, the U.S. Environmental Protection Agency (EPA) Stormwater Management Model (SWMM). SWMM is often used in watershed studies that are uncalibrated or calibrated to the overall runoff-reduction from multiple bioretention or LID practices in the watershed. This study is unique by calibrating the SWMM LID module to a single bioretention cell with more focus on the hydrologic pathways and the outflows produced by the model. The SWMM LID module performed better than DRAINMOD-Urban for event volumes of both drainage and overflow. SWMM also had better NSEs for overflow hydrographs. However, visual inspection of the hydrographs showed that both models achieved good timing and hydrograph shape, but SWMM predicted peak flow closer to the measured peak overflow. DRAINMOD-Urban produced drainage hydrographs that best matched the measure hydrograph shape which was confirmed with the highest NSE values. SWMM was unsuccessful in predicting measured drainage hydrographs because the percolation and exfiltration procedures in SWMM that caused rectangular-shaped hydrographs when the bioretention cell was saturated. Additionally, SWMM users must choose between calibrating the model for hydrographs or volumes. The advantage of DRAINMOD-Urban is that both the drainage and overflow volumes improved with the hydrograph calibration. Therefore, this study revealed that DRAINMOD-Urban could be more advantageous at the site-scale for modeling bioretention hydrographs but if the application only requires event volumes then SWMM is a good option. However, hydrographs are most critical when watershed-scale impacts are being investigated such as routing flows to other structures downstream. Therefore, a combination of the bioretention hydrology in DRAINMOD-Urban and the hydraulics of SWMM would be a significant improvement to the field of bioretention modeling.

Chapter 4 examined the most intensive input parameters required in DRAINMOD-Urban, the SWCC and Ksat. These two soil properties require lengthy laboratory tests that could hinder model usage. Therefore, estimations of these properties called pedotransfer functions were investigated to determine if they could reliably be used as substitutions for measured SWCC and Ksat in DRAINMOD-Urban. The pedotransfer functions (PTF) used in this study were the Vereecken and ROSETTA PTFs for the SWCC and the ROSETTA PTF for Ksat. The best DRAINMOD-Urban performance from a PTF was the ROSETTA SWCC (using the calibrated Ksat) which matched the drainage hydrograph performance of the measured SWCC in DRAINMOD-Urban at NSE=0.59 and 0.6, respectively. The overflow hydrograph performance from the ROSETTA SWCC was slightly improved at NSE=-0.06 compared to NSE=-0.10 from the measured SWCC. In fact, ROSETTA had the best overflow performance for all simulations. The Vereecken PTF showed the worst drainage hydrograph performance (NSE=0.44-0.49) in almost all scenarios but still performed above NSE=0.4 which has been suggested as a limit for acceptable performance at an daily timestep (Skaggs et al., 2012). Visual inspection of the hydrographs verified these results and showed little change in the overflow or drainage hydrograph shape across all scenarios. Event volumes had similar patterns of performance. DRAINMOD-Urban performed best for drainage and overflow volumes with the measured SWCC (drainage NSE=0.83, overflow NSE=0.66) and the ROSETTA PTF (drainage NSE=0.73, overflow NSE=0.68) respectively under that calibrated Ksat. This shows that the measured SWCC can be substituted by a SWCC calculated by the ROSETTA PTF without affecting model results. This could lead to more usage of DRAINMOD-Urban as a bioretention model by eliminating the need for detailed soil measurements.

Each of these studies has provided evidence that DRAINMOD-Urban is successful in enhancing bioretention modeling. This model has been vigorously tested under a variety of scenarios including changes in temporal scale, calibration strategies, and soil parameters. Chapter 2 demonstrated a strong influence of scale on model performance and calibration approaches. The intended application can affect which scale and calibration strategy should be used in the model such as if output volumes or hydrographs are the priority.

Both cumulative event volumes and continuous event hydrographs of the drainage and overflow outflows were evaluated in these studies to consider different modeling applications. When used at a single site or for a quick runoff reduction analysis, event volumes may suffice. However, the dynamic behavior of bioretention hydrology should be considered in watershed studies where downstream structures, LID practices, or stream response could be affected by the timing and intensity of flow upstream. Furthermore, many watershed studies do not evaluate performance of individual practices but lump results into a single estimation of runoff from the watershed. If these watersheds are evaluated for flow behavior instead of volume, then individual practices need to accurately model flow dynamics before it is expanded to a watershed scale. This could be done as suggested in Chapter 3 by combining a site-scale model like DRAINMOD-Urban with a watershed model like SWMM. However, more calibration studies for both of these models are needed to validate the model performance seen in these studies to more field locations, bioretention design elements, and particularly, more overflow events.

Model usability was also considered for DRAINMOD-Urban by considering alternative methods for determining the two most cumbersome input parameters, the SWCC and Ksat. By showing similar model performance with the SWCC derived by the ROSETTA PTF, DRAINMOD-Urban can be applied to more studies where soil data availability and/or sample processing restricted its usage. DRAINMOD-Urban usage could also be improved through more sensitivity analysis of calibration parameters and soil properties. Understanding the sensitivity of model parameters helps users know which parameters have the largest impact on model outputs and therefore, how to prioritize quantifying these inputs accurately.

It was the aim of this dissertation to evaluate DRAINMOD-Urban for bioretention modeling with the hope that DRAINMOD-Urban will be adopted in future studies. The robust combination of studies in this dissertation corroborates that DRAINMOD-Urban is comparable to other bioretention models and, ultimately, is well-suited to modeling the flashy nature of urban bioretention systems.

REFERENCES

Aad, M.P.A., Suidan, M.T. and Shuster, W.D. (2010) Modeling Techniques of Best Management Practices: Rain Barrels and Rain Gardens Using EPA SWMM-5. Journal of Hydrologic Engineering 15(6), 434-443. https://doi.org/10.1061/(Asce)He.1943-5584.0000136

Akan, A.O. (2013) Preliminary Design Aid for Bioretention Filters. Journal of Hydrologic Engineering 18(3), 318-323. https://doi.org/10.1061/(Asce)He.1943-5584.0000554

Al-Ameri, M., Hatt, B., Le Coustumer, S., Fletcher, T., Payne, E. and Deletic, A. (2018) Accumulation of Heavy Metals in Stormwater Bioretention Media: A Field Study of Temporal and Spatial Variation. Journal of Hydrology 567, 721-731. https://doi.org/10.1016/j.jhydrol.2018.03.027

Alexander, M.D., Barfield, B.J., Hayes, J.C., Harp, S.L., Chalavadi, M., Yeri, S., Stevens, E. and Bates, B.T. (2011) Modeling Low Impact Development Water Quality BMPs with IDEAL. Beighley II, R.E. and Killgore, M.W. (eds), American Society of Civil Engineers, Palm Springs, CA.

Asleson, B.C., Nestingen, R.S., Gulliver, J.S., Hozalski, R.M. and Nieber, J.L. (2009) Performance Assessment of Rain Gardens(1). Journal of the American Water Resources Association 45(4), 1019-1031. https://doi.org/10.1111/j.1752-1688.2009.00344.x

ASTM (2007) Standard Test Method for Particle-Size Analysis of Soils (Astm D422-63).

ASTM (2014) Standard Test Methods for Moisture, Ash, and Organic Matter of Peat and Other Organic Soils (Astmd2974-14).

ASTM (2018) Standard Test Methods for Laboratory Determination of Density (Unit Weight) of Soil Specimens (Astm D7263-09(2018)E2), ASTM International, West Conshohocken, PA.

Atchison, D., Potter, K. and Severson, L. (2006) Design Guidelines for Stormwater Bioretention Facilities. White, E. and Wittman, S. (eds), Water Resources Institute, University of Wisconsin.

Avellaneda, P.M., Jefferson, A.J., Grieser, J.M. and Bush, S.A. (2017) Simulation of the Cumulative Hydrological Response to Green Infrastructure. Water Resources Research 53(4), 3087-3101. https://doi.org/10.1002/2016wr019836

Baffaut, C., M. Dabney, S., D. Smolen, M., A. Youssef, M., V. Bonta, J., L. Chu, M., A. Guzman, J., S. Shedekar, V., K. Jha, M. and G. Arnold, J. (2015) Hydrologic and Water Quality Modeling: Spatial and Temporal Considerations. Transactions of the ASABE 58(6), 1661-1680. https://doi.org/https://doi.org/10.13031/trans.58.10714

Bai, Y., Wagener, T. and Reed, P. (2009) A Top-Down Framework for Watershed Model Evaluation and Selection under Uncertainty. Environmental Modelling & Software 24(8), 901-916. https://doi.org/10.1016/j.envsoft.2008.12.012

Barbu, I.A. and Ballestero, T.P. (2015) Unsaturated Flow Functions for Filter Media Used in Low-Impact Development—Stormwater Management Systems. Journal of Irrigation and Drainage Engineering 141(1), 04014041. https://doi.org/10.1061/(asce)ir.1943-4774.0000766

Barbu, I.A., Ballestero, T.P. and Roseen, R.M. (2009) LID-Swm Practices as a Means of Resilience to Climate Change and Its Effects on Groundwater Recharge. Steve Starrett, P.D., P.E. (ed), ASCE, Kansas City, MO.

Basu, N.B., Thompson, S.E. and Rao, P.S.C. (2011) Hydrologic and Biogeochemical Functioning of Intensively Managed Catchments: A Synthesis of Top-Down Analyses. Water Resources Research 47. https://doi.org/Artn W00j1510.1029/2011wr010800

Bhave, A.G., Mishra, A. and Raghuwanshi, N.S. (2014) A Combined Bottom-up and Top-Down Approach for Assessment of Climate Change Adaptation Options. Journal of Hydrology 518, 150-161. https://doi.org/10.1016/j.jhydrol.2013.08.039

Boancă, P., Dumitraș, A., Luca, L., Bors-Oprișa, S. and Laczi, E. (2018) Analysing Bioretention Hydraulics and Runoff Retention through Numerical Modelling Using RECARGA: A Case Study in a Romanian Urban Area. Polish Journal of Environmental Studies 27(5), 1965-1973. https://doi.org/10.15244/pjoes/79271

Bonneau, J., Fletcher, T.D., Costelloe, J.F., Poelsma, P.J., James, R.B. and Burns, M.J. (2018) Where Does Infiltrated Stormwater Go? Interactions with Vegetation and Subsurface Anthropogenic Features. Journal of Hydrology 567, 121-132. https://doi.org/10.1016/j.jhydrol.2018.10.006

Bosley, E.K. (2008) Hydrologic Evaluation of Low Impact Development Using a Continuous, Spatially-Distributed Model.

Braga, A., Horst, M. and Traver, R.G. (2007) Temperature Effects on the Infiltration Rate through an Infiltration Basin BMP. Journal of Irrigation and Drainage Engineering 133(6), 593-601. https://doi.org/10.1061/(Asce)0733-9437(2007)133:6(593)

Broekhuizen, I., Leonhardt, G., Marsalek, J. and Viklander, M. (2020) Event Selection and Two-Stage Approach for Calibrating Models of Green Urban Drainage Systems. Hydrol. Earth Syst. Sci. 24(2), 869-885. https://doi.org/10.5194/hess-24-869-2020

Brown, R.A. (2011) Evaluation of Bioretention Hydrology and Pollutant Removal in the Upper Coastal Plain of North Carolina with Development of a Bioretention Modeling Application in DRAINMOD. Doctoral dissertation, North Carolina State University, Raleigh, North Carolina.

Brown, R.A., Birgand, F. and Hunt, W.F. (2013a) Analysis of Consecutive Events for Nutrient and Sediment Treatment in Field-Monitored Bioretention Cells. Water Air and Soil Pollution 224(6). https://doi.org/ARTN 158110.1007/s11270-013-1581-6

Brown, R.A. and Hunt, W.F. (2010) Impacts of Construction Activity on Bioretention Performance. Journal of Hydrologic Engineering 15(6), 386-394. https://doi.org/10.1061/(Asce)He.1943-5584.0000165

Brown, R.A. and Hunt, W.F. (2011a) Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells. Journal of Irrigation and Drainage Engineering 137(3), 132-143. https://doi.org/10.1061/(Asce)Ir.1943-4774.0000167

Brown, R.A. and Hunt, W.F. (2011b) Underdrain Configuration to Enhance Bioretention Exfiltration to Reduce Pollutant Loads. Journal of Environmental Engineering-Asce 137(11), 1082-1091. https://doi.org/10.1061/(Asce)Ee.1943-7870.0000437

Brown, R.A. and Hunt, W.F. (2012) Improving Bioretention/Biofiltration Performance with Restorative Maintenance. Water Science and Technology 65(2), 361-367. https://doi.org/10.2166/wst.2012.860

Brown, R.A., Skaggs, R.W. and Hunt, W.F. (2013b) Calibration and Validation of DRAINMOD to Model Bioretention Hydrology. Journal of Hydrology 486, 430-442. https://doi.org/10.1016/j.jhydrol.2013.02.017

Burns, M.J., Fletcher, T.D., Walsh, C.J., Ladson, A.R. and Hatt, B.E. (2012) Hydrologic Shortcomings of Conventional Urban Stormwater Management and Opportunities for Reform. Landscape and Urban Planning 105(3), 230-240. https://doi.org/10.1016/j.landurbplan.2011.12.012

Carsel, R.F. and Parrish, R.S. (1988) Developing Joint Probability-Distributions of Soil-Water Retention Characteristics. Water Resources Research 24(5), 755-769. https://doi.org/DOI 10.1029/WR024i005p00755

Center for Neighborhood Technology (2007) Green Values Stormwater Calculator Methodology, Center for Neighborhood Technology, greenvalues.cnt.org.

Chapman, C. and Horner, R.R. (2010) Performance Assessment of a Street-Drainage Bioretention System. Water Environment Research 82(2), 109-119. https://doi.org/10.2175/106143009x426112

Chiew, F.H.S. and McMahon, T.A. (1997) Modelling Daily Runoff and Pollutant Load from Urban Catchments. Water 24, 16-17.

Christianson, R.D. (2003) Evaluation of the Soil and Water Assessment Tool for Urban Stormwater Management, Kansas State University, Manhattan, KS.

Dagenais, D., Brisson, J. and Fletcher, T.D. (2018) The Role of Plants in Bioretention Systems; Does the Science Underpin Current Guidance? Ecological Engineering 120, 532-545. https://doi.org/10.1016/j.ecoleng.2018.07.007

Davis, A.P. (2007) Field Performance of Bioretention: Water Quality. Environmental Engineering Science 24(8), 1048-1064. https://doi.org/10.1089/ees.2006.0190

Davis, A.P. (2008) Field Performance of Bioretention: Hydrology Impacts. Journal of Hydrologic Engineering 13(2), 90-95. https://doi.org/10.1061/(Asce)1084-0699(2008)13:2(90)

Davis, A.P., Hunt, W.F., Traver, R.G. and Clar, M. (2009) Bioretention Technology: Overview of Current Practice and Future Needs. Journal of Environmental Engineering 135(3), 109-117. https://doi.org/10.1061//ASCE/0733-9372/2009/135:3/109

Davis, A.P., Shokouhian, M., Sharma, H. and Minami, C. (2006) Water Quality Improvement through Bioretention Media: Nitrogen and Phosphorus Removal. Water Environment Research 78(3), 284-293. https://doi.org/10.2175/106143005x94376

Davis, A.P., Traver, R.G., Hunt, W.F., Lee, R., Brown, R.A. and Olszewski, J.M. (2012) Hydrologic Performance of Bioretention Storm-Water Control Measures. Journal of Hydrologic Engineering 17(5), 604-614. https://doi.org/10.1061/(Asce)He.1943-5584.0000467

DeGasperi, C.L. (2009) Development of a Stormwater Retrofit Plan for Water Resources Inventory Area 9: SUSTAIN Model Pilot Study. Division, K.C.W.a.L.R. (ed), King County Department of Natural Resources and Parks, Seattle, WA.

DHI (2017) MIKE URBAN: Collection System-Modelling of Storm Water Drainage Networks and Sewer Collection Systems, User Guide.

Dietrich, A., Yarlagadda, R. and Gruden, C. (2017) Estimating the Potential Benefits of Green Stormwater Infrastructure on Developed Sites Using Hydrologic Model Simulation. Environmental Progress & Sustainable Energy 36(2), 557-564. https://doi.org/10.1002/ep.12428

Dietz, M.E. (2007) Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. Water, Air, and Soil Pollution 186(1-4), 351-363. https://doi.org/10.1007/s11270-007-9484-z

Domenico, P.A. and Schwartz, F.W. (1990) Physical and Chenical Hydrogeology, John Wiley and Sons, New York.

Dotto, C.B.S., Deletic, A., McCarthy, D.T. and Fletcher, T.D. (2011) Calibration and Sensitivity Analysis of Urban Drainage Models: Music Rainfall/Runoff Module and a Simple Stormwater Quality Model. Australasian Journal of Water Resources 15(1), 85-94. https://doi.org/10.1080/13241583.2011.11465392

DRAINMOD 6.1 Help File (2013), North Carolina State University.

Dussaillant, A., Cozzetto, K., Brander, K. and Potter, K. (2003) Green-Ampt Model of a Rain Garden and Comparison to Richard's Equation Model. Transactions on Ecology and the Environment 67, 891-900.

Elliott, A. and Trowsdale, S. (2007) A Review of Models for Low Impact Urban Stormwater Drainage. Environmental Modelling & Software 22(3), 394-405. https://doi.org/10.1016/j.envsoft.2005.12.005

Elliott, A.H., Trowsdale, S.A. and Wadhwa, S. (2009) Effect of Aggregation of on-Site Storm-Water Control

Devices in an Urban Catchment Model. Journal of Hydrologic Engineering, 14(9), 975-983. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000064

Emerson, C.H. and Traver, R.G. (2008) Multiyear and Seasonal Variation of Infiltration from Storm-Water Best Management Practices. Journal of Irrigation and Drainage Engineering 134(5), 598-605. https://doi.org/10.1061/(Asce)0733-9437(2008)134:5(598)

Engel, J. and Hoonhout, H.C.M. (2007) Statistics Development: Statistical Methods Meeting the User's Needs. Asta-Advances in Statistical Analysis 91(4), 413-427. https://doi.org/10.1007/s10182-007-0046-x

EPA SWMM Help File 5.1 (2017), U.S. Environmental Protection Agency,, Washington, DC.

Ergas, S.J., Sengupta, S., Siege, R., Pandit, A., Yao, Y.F. and Yuan, X. (2010) Performance of Nitrogen-Removing Bioretention Systems for Control of Agricultural Runoff. Journal of Environmental Engineering-Asce 136(10), 1105-1112. https://doi.org/10.1061/(Asce)Ee.1943-7870.0000243

eWater (2013) MUSIC by Ewater: User Manual.

Feddes, R.A., Kowalik, P.J. and Zaradny, H. (1978) Simulation of Field Water Use and Crop Yield, John Wiley & Sons, New York, NY.

Fletcher, T.D., Shuster, W., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J.-L., Mikkelsen, P.S., Rivard, G., Uhl, M., Dagenais, D. and Viklander, M. (2014) SUDS, LID, BMPs, WSUD and More – the Evolution and Application of Terminology Surrounding Urban Drainage. Urban Water Journal 12(7), 525-542. https://doi.org/10.1080/1573062x.2014.916314

Gagrani, V., Diemer, J.A., Karl, J.J. and Allan, C.J. (2014) Assessing the Hydrologic and Water Quality Benefits of a Network of Stormwater Control Measures in a Se U.S. Piedmont Watershed. JAWRA Journal of the American Water Resources Association 50(1), 128-142. https://doi.org/10.1111/jawr.12121

Gao, J., Pan, J., Hu, N. and Xie, C. (2018) Hydrologic Performance of Bioretention in an Expressway Service Area. Water Sci Technol 77(7-8), 1829-1837. https://doi.org/10.2166/wst.2018.048

Garcia-Gutierrez, C., Pachepsky, Y. and Martin, M.A. (2018) Technical Note: Saturated Hydraulic Conductivity and Textural Heterogeneity of Soils. Hydrology and Earth System Sciences 22(7), 3923-3932. https://doi.org/10.5194/hess-22-3923-2018

Goh, H.W., Zakaria, N.A., Lau, T.L., Foo, K.Y., Chang, C.K. and Leow, C.S. (2017) Mesocosm Study of Enhanced Bioretention Media in Treating Nutrient Rich Stormwater for Mixed Development Area. Urban Water Journal 14(2), 134-142. https://doi.org/10.1080/1573062x.2015.1076861

Good, J.F., O'Sullivan, A.D., Wicke, D. and Cochrane, T.A. (2012) Contaminant Removal and Hydraulic Conductivity of Laboratory Rain Garden Systems for Stormwater Treatment. Water Science and Technology 65(12), 2154-2161. https://doi.org/10.2166/wst.2012.135

Green, W.H. and Ampt, G. (1911) Studies of Soil Physics: Part 1. J. Agric. Sci. 4(1), 1-24.

Gulbaz, S. and Kazezyilmaz-Alhan, C.M. (2017) An Evaluation of Hydrologic Modeling Performance of EPA SWMM for Bioretention. Water Sci Technol 76(11), 3035-3043. https://doi.org/10.2166/wst.2017.464

Gülbaz, S. and Kazezyılmaz-Alhan, C.M. (2017) Hydrological Model of LID with Rainfall-Watershed-Bioretention System. Water Resources Management 31(6), 1931-1946. https://doi.org/10.1007/s11269-017-1622-9

Guo, J.C.Y. and Luu, T.M. (2015) Hydrologic Model Developed for Stormwater Infiltration Practices. Journal of Hydrologic Engineering 20(9), 06015001. https://doi.org/10.1061/(asce)he.1943-5584.0001161

Gwenzi, W., Hinz, C., Holmes, K., Phillips, I.R. and Mullins, I.J. (2011) Field-Scale Spatial Variability of Saturated Hydraulic Conductivity on a Recently Constructed Artificial Ecosystem. Geoderma 166(1), 43-56. https://doi.org/10.1016/j.geoderma.2011.06.010

Hamel, P. and Fletcher, T.D. (2014a) The Impact of Stormwater Source-Control Strategies on the (Low) Flow Regime of Urban Catchments. Water Sci Technol 69(4), 739-745. https://doi.org/10.2166/wst.2013.772

Hamel, P. and Fletcher, T.D. (2014b) Modelling the Impact of Stormwater Source Control Infiltration Techniques on Catchment Baseflow. Hydrological Processes 28(24), 5817-5831. https://doi.org/10.1002/hyp.10069

Hathaway, J.M., Brown, R.A., Fu, J.S. and Hunt, W.F. (2014) Bioretention Function under Climate Change Scenarios in North Carolina, USA. Journal of Hydrology 519, 503-511. https://doi.org/10.1016/j.jhydrol.2014.07.037

Hatt, B.E., Fletcher, T.D. and Deletic, A. (2009) Hydrologic and Pollutant Removal Performance of Stormwater Biofiltration Systems at the Field Scale. Journal of Hydrology 365(3-4), 310-321. https://doi.org/10.1016/j.jhydrol.2008.12.001

He, Z.X. and Davis, A.P. (2011) Process Modeling of Storm-Water Flow in a Bioretention Cell. Journal of Irrigation and Drainage Engineering 137(3), 121-131. https://doi.org/10.1061/(Asce)Ir.1943-4774.0000166

Heasom, W., Traver, R.G. and Welker, A.L. (2006) Hydrologic Modeling of a Bioinfiltration Best Management Practice. Journal of the American Water Resources Association 42(5), 1329-1347. https://doi.org/DOI 10.1111/j.1752-1688.2006.tb05304.x

Hrachowitz, M. and Clark, M.P. (2017) Hess Opinions: The Complementary Merits of Competing Modelling Philosophies in Hydrology. Hydrology and Earth System Sciences 21(8), 3953-3973. https://doi.org/10.5194/hess-21-3953-2017

Hsieh, C.H. and Davis, A.P. (2005) Multiple-Event Study of Bioretention for Treatment of Urban Storm Water Runoff. Water Science and Technology 51(3-4), 177-181. <Go to ISI>://WOS:000228827100023

Hsieh, C.H., Davis, A.P. and Needelman, B.A. (2007a) Bioretention Column Studies of Phosphorus Removal from Urban Stormwater Runoff. Water Environment Research 79(2), 177-184. https://doi.org/10.2175/106143006x111745

Hsieh, C.H., Davis, A.P. and Needelman, B.A. (2007b) Nitrogen Removal from Urban Stormwater Runoff through Layered Bioretention Columns. Water Environment Research 79(12), 2404-2411. https://doi.org/10.2175/106143007x183844

Hunt, W.F., Jarrett, A.R., Smith, J.T. and Sharkey, L.J. (2006) Evaluating Bioretention Hydrology and Nutrient Removal at Three Field Sites in North Carolina. Journal of Irrigation and Drainage Engineering 132(6), 600-608. https://doi.org/10.1061/(Asce)0733-9437(2006)132:6(600)

Hunt, W.F., Kannan, N., Jeong, J. and Gassman, P.W. (2009) Stormwater Best Management Practices: Review of Current Practices and Potential Incorporation in SWAT. International Agricultural Engineering Journal 18(1-2), 73-89.

Hunt, W.F., Smith, J.T., Jadlocki, S.J., Hathaway, J.M. and Eubanks, P.R. (2008) Pollutant Removal and Peak Flow Mitigation by a Bioretention Cell in Urban Charlotte, Nc. Journal of Environmental Engineering-Asce 134(5), 403-408. https://doi.org/10.1061/(Asce)0733-9372(2008)134:5(403)

Imteaz, M.A., Ahsan, A., Rahman, A. and Mekanik, F. (2013) Modelling Stormwater Treatment Systems Using MUSIC: Accuracy. Resources, Conservation and Recycling 71, 15-21. https://doi.org/10.1016/j.resconrec.2012.11.007

Jarvis, P.G. (1993) Scaling Physiological Processes: Leaf to Globe. J.R., E. and C.B., F. (eds), Academic Press.

Jayasooriya, V.M. and Ng, A.W.M. (2014) Tools for Modeling of Stormwater Management and Economics of Green Infrastructure Practices: A Review. Water, Air, & Soil Pollution 225(8). https://doi.org/10.1007/s11270-014-2055-1

Jefferson, A.J., Bhaskar, A.S., Hopkins, K.G., Fanelli, R., Avellaneda, P.M. and McMillan, S.K. (2017) Stormwater Management Network Effectiveness and Implications for Urban Watershed Function: A Critical Review. Hydrological Processes 31(23), 4056-4080. https://doi.org/10.1002/hyp.11347

Jeong, J., Kannan, N., Arnold, J., Glick, R., Gosselink, L. and Srinivasan, R. (2010) Development and Integration of Sub-Hourly Rainfall–Runoff Modeling Capability within a Watershed Model. Water Resources Management 24(15), 4505-4527. https://doi.org/10.1007/s11269-010-9670-4

Jiang, C.B., Li, J.K., Li, H.E., Li, Y.J. and Chen, L. (2017) Field Performance of Bioretention Systems for Runoff Quantity Regulation and Pollutant Removal. Water Air and Soil Pollution 228(12). https://doi.org/ARTN 46810.1007/s11270-017-3636-6

Kabbes, K.C., McCracken, S. and Hood, J.W. (2008) Determining Cost Effective Pollution Reduction BMP Scenarios for Low Impact Redevelopment and a Watershed Plan Using Winslamm, Seattle, WA.

Kaykhosravi, S., Khan, U. and Jadidi, A. (2018) A Comprehensive Review of Low Impact Development Models for Research, Conceptual, Preliminary and Detailed Design Applications. Water 10(11), 1541. https://doi.org/10.3390/w10111541

Khaniya, B., Wanniarachchi, S. and Rathnayake, U. (2017) Importance of Hydrologic Simulation for Lids and BMPs Design Using Hec-Hms: A Case Demonstration. International Journal of Hydrology 1(5), 138-146.

Kim, H., Mallari, K.J.B., Baek, J., Pak, G., Choi, H.I. and Yoon, J. (2019) Considering the Effect of Groundwater on Bioretention Using the Storm Water Management Model. J Environ Manage 231, 1270-1276. https://doi.org/10.1016/j.jenvman.2018.03.032

Kirkham, D. (1957) Drainage of Agricultural Lands. Luthin, J.N. (ed), pp. 139-181, ASA, Madison, WI.

Kirkham, M.B. (2005) Principles of Soil and Plant Water Relations. Kirkham, M.B. (ed), pp. 101-115, Academic Press, Burlington.

Klemes, V. (1983) Conceptualization and Scale in Hydrology. Journal of Hydrology 65(1-3), 1-23. https://doi.org/Doi 10.1016/0022-1694(83)90208-1

Kluge, B., Markert, A., Facklam, M., Sommer, H., Kaiser, M., Pallasch, M. and Wessolek, G. (2018) Metal Accumulation and Hydraulic Performance of Bioretention Systems after Long-Term Operation. Journal of Soils and Sediments 18(2), 431-441. https://doi.org/10.1007/s11368-016-1533-z

Klute, A. (1986) Methods of Soil Analysis. Part 1: Physical and Mineralogical Methods. Klute, A. (ed), pp. 635–662, Soil Science Society of America, Madison, WI.

Komlos, J. and Traver, R.G. (2012) Long-Term Orthophosphate Removal in a Field-Scale Storm-Water Bioinfiltration Rain Garden. Journal of Environmental Engineering 138(10), 991-998. https://doi.org/10.1061/(Asce)Ee.1943-7870.0000566

Kottek, M., Grieser, J., Beck, C., Rudolf, B. and Rubel, F. (2006) World Map of the Köppen-Geiger Climate Classification Updated. Meteorologische Zeitschrift 15(3), 259-263.

Krause, P., Boyle, D.P. and Base, F. (2005) Comparison of Different Efficiency Criteria for Hydrological Model Assessment. Advances in Geosciences, 5, 89-97.

L-Thia Low Impact Development Spreadsheet (2015), Purdue University.

Lai, F.-h., Shoemaker, L., Alvi, K., Riverson, J. and Zhen, J.X. (2010) Current Capabilities and Planned Enhancements of SUSTAIN. Palmer, R.N. (ed), Providence, RI.

Lee, J.G., Selvakumar, A., Alvi, K., Riverson, J., Zhen, J.X., Shoemaker, L. and Lai, F.-h. (2012) A Watershed-Scale Design Optimization Model for Stormwater Best Management Practices. Environmental Modelling & Software 37, 6-18. https://doi.org/10.1016/j.envsoft.2012.04.011

Lee, R.S., Traver, R.G. and Welker, A.L. (2013) Continuous Modeling of Bioinfiltration Storm-Water Control Measures Using Green and Ampt. Journal of Irrigation and Drainage Engineering 139(12), 1004-1010. https://doi.org/10.1061/(asce)ir.1943-4774.0000651

Legates, D.R. and McCabe, G.J. (1999) Evaluating the Use of "Goodness-of-Fit" Measures in Hydrologic and Hydroclimatic Model Validation. Water Resources Research 35(1), 233-241. https://doi.org/Doi 10.1029/1998wr900018

Li, C., Fletcher, T.D., Duncan, H.P. and Burns, M.J. (2017) Can Stormwater Control Measures Restore Altered Urban Flow Regimes at the Catchment Scale? Journal of Hydrology 2017 v.549, pp. 631-653. https://doi.org/10.1016/j.jhydrol.2017.03.037

Li, H. and Davis, A.P. (2008a) Urban Particle Capture in Bioretention Media. I: Laboratory and Field Studies. Journal of Environmental Engineering-Asce 134(6), 409-418. https://doi.org/10.1061/(Asce)0733-9372(2008)134:6(409)

Li, H. and Davis, A.P. (2008b) Urban Particle Capture in Bioretention Media. Ii: Theory and Model Development. Journal of Environmental Engineering-Asce 134(6), 419-432. https://doi.org/10.1061/(Asce)0733-9372(2008)134:6(419)

Li, H. and Davis, A.P. (2009) Water Quality Improvement through Reductions of Pollutant Loads Using Bioretention. Journal of Environmental Engineering 135(8), 567-576. https://doi.org/10.1061/(Asce)Ee.1943-7870.0000026

Li, H. and De Costa, G. (2016) Analysing Rain Garden Infiltration Efficiency Using MOUSE Model.

Li, H., Sharkey, L.J., Hunt, W.F. and Davis, A.P. (2009) Mitigation of Impervious Surface Hydrology Using Bioretention in North Carolina and Maryland. Journal of Hydrologic Engineering 14(4), 407-415. https://doi.org/10.1061/(Asce)1084-0699(2009)14:4(407)

Li, J., Zhao, R., Li, Y. and Chen, L. (2018) Modeling the Effects of Parameter Optimization on Three Bioretention Tanks Using the HYDRUS-1d Model. J Environ Manage 217, 38-46. https://doi.org/10.1016/j.jenvman.2018.03.078

Li, K., De Jong, R. and Boisvert, J. (2001) Comparison of Root-Water-Uptake Models.

Li, Z.Y. and Lam, K.M. (2015) Statistical Evaluation of Bioretention System for Hydrologic Performance. Water Science and Technology 71(11), 1742-1749. https://doi.org/10.2166/wst.2015.131

Liao, K.H., Xu, S.H., Wu, J.C., Ji, S.H. and Lin, Q. (2011) Assessing Soil Water Retention Characteristics and Their Spatial Variability Using Pedotransfer Functions. Pedosphere 21(4), 413-422. https://doi.org/Doi 10.1016/S1002-0160(11)60143-4

Line, D.E. and Hunt, W.F. (2009) Performance of a Bioretention Area and a Level Spreader-Grass Filter Strip at Two Highway Sites in North Carolina. Journal of Irrigation and Drainage Engineering 135(2), 217-224. https://doi.org/10.1061/(Asce)0733-9437(2009)135:2(217)

Lisenbee, W., Hathaway, J., Negm, L., Youssef, M. and Winston, R. (2020) Enhanced Bioretention Cell Modeling with DRAINMOD-Urban: Moving from Water Balances to Hydrograph Production. Journal of Hydrology 582, 124491. https://doi.org/10.1016/j.jhydrol.2019.124491

Liu, J., Sample, D., Bell, C. and Guan, Y. (2014a) Review and Research Needs of Bioretention Used for the Treatment of Urban Stormwater. Water 6(4), 1069-1099. https://doi.org/10.3390/w6041069

Liu, J., Sample, D.J., Owen, J.S., Li, J.L. and Evanylo, G. (2014b) Assessment of Selected Bioretention Blends for Nutrient Retention Using Mesocosm Experiments. Journal of Environmental Quality 43(5), 1754-1763. https://doi.org/10.2134/jeq2014.01.0017

Liu, R.F. and Fassman-Beck, E. (2017) Hydrologic Experiments and Modeling of Two Laboratory Bioretention Systems under Different Boundary Conditions. Frontiers of Environmental Science & Engineering 11(4). https://doi.org/ARTN 1010.1007/s11783-017-0951-5

Lopez, E.V., Lynn, T.J., Peterson, M., Ergas, S.J., Trotz, M.A. and Mihelcic, J.R. (2016) Enhanced Nutrient Management of Stormwater through a Field Demonstration of Nitrogen Removal in a Modified Bioretention System. World Environmental and Water Resources Congress 2016: Environmental, Sustainability, Groundwater, Hydraulic Fracturing, and Water Distribution Systems Analysis, 60-69. <Go to ISI>://WOS:000389439700007

Lucas, W. (2008) Continuous Simulation of Integrated Bioretention-Infiltration Systems for Urban Retrofits, Seattle, WA.

Lucas, W. (2010) Design of Integrated Bioinfiltration-Detention Urban Retrofits with Design Storm and Continuous Simulation Methods. J. Hydrol. Eng. 15(6), 486-498. https://doi.org/10.1061//ASCE/HE.1943-5584.0000137

Lucas, W.C. and Greenway, M. (2008) Nutrient Retention in Vegetated and Nonvegetated Bioretention Mesocosms. Journal of Irrigation and Drainage Engineering 134(5), 613-623. https://doi.org/10.1061/(Asce)0733-9437(2008)134:5(613)

Lucas, W.C. and Greenway, M. (2011a) Hydraulic Response and Nitrogen Retention in Bioretention Mesocosms with Regulated Outlets: Part I-Hydraulic Response. Water Environment Research 83(8), 692-702. https://doi.org/10.2175/106143010x12780288628697

Lucas, W.C. and Greenway, M. (2011b) Hydraulic Response and Nitrogen Retention in Bioretention Mesocosms with Regulated Outlets: Part Ii-Nitrogen Retention. Water Environment Research 83(8), 703-713. https://doi.org/10.2175/106143011x12989211840936

Lucas, W.C. and Greenway, M. (2011c) Phosphorus Retention by Bioretention Mesocosms Using Media Formulated for Phosphorus Sorption: Response to Accelerated Loads. Journal of Irrigation and Drainage Engineering 137(3), 144-153. https://doi.org/10.1061/(Asce)Ir.1943-4774.0000243

Lucke, T., Dierkes, C. and Boogaard, F. (2017) Investigation into the Long-Term Stormwater Pollution Removal Efficiency of Bioretention Systems. Water Science and Technology 76(8), 2133-2139. https://doi.org/10.2166/wst.2017.382

Lucke, T. and Nichols, P.W.B. (2015) The Pollution Removal and Stormwater Reduction Performance of Street-Side Bioretention Basins after Ten Years in Operation. Science of the Total Environment 536, 784-792. https://doi.org/10.1016/j.scitotenv.2015.07.142

Lynn, T.J., Nachabe, M.H. and Ergas, S.J. (2018) Swmm5 Unsaturated Drainage Models for Stormwater Biofiltration with an Internal Water Storage Zone. Journal of Sustainable Water in the Built Environment 4(1), 04017018. https://doi.org/10.1061/jswbay.0000844

Machusick, M., Welker, A. and Traver, R. (2011) Groundwater Mounding at a Storm-Water Infiltration BMP. Journal of Irrigation and Drainage Engineering 137(3), 154-160. https://doi.org/10.1061/(Asce)Ir.1943-4774.0000184

Massoudieh, A. and Aflak, S. (2017) User's Manual for Green Infrastructure Flexible Model (GIFMod).

Massoudieh, A., Maghrebi, M., Kamrani, B., Nietch, C., Tryby, M., Aflaki, S. and Panguluri, S. (2017) A Flexible Modeling Framework for Hydraulic and Water Quality Performance Assessment of Stormwater Green Infrastructure. Environmental Modelling & Software 92, 57-73. https://doi.org/10.1016/j.envsoft.2017.02.013

McCutcheon, M. and Wride, D. (2013) Shades of Green: Using SWMM LID Controls to Simulate Green Infrastructure. Journal of Water Management Modeling. https://doi.org/10.14796/jwmm.r246-15

Meng, Y., Wang, H., Chen, J. and Zhang, S. (2014) Modelling Hydrology of a Single Bioretention System with HYDRUS-1d. ScientificWorldJournal 2014, 521047. https://doi.org/10.1155/2014/521047

Montgomery, R.J., Gaffield, S.J., Sigmarrson, S.G., Severson, L.M. and Lefers, J.D. (2010) The Challenges of Mitigating Hydrologic Impacts of Development: Lessons Learned in Dane County, Wisconsin, American Society of Civil Engineers, Madison, WI.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L. (2007) Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations. Transactions of the ASABE 50(3), 885-900. <Go to ISI>://WOS:000248036800021

Mualem, Y. (1977) Extension of Similarity Hypothesis Used for Modeling Soil-Water Characteristics. Water Resources Research 13(4), 773-780. https://doi.org/DOI 10.1029/WR013i004p00773

Muthanna, T.M., Viklander, M. and Thorolfsson, S.T. (2007) An Evaluation of Applying Existing Bioretention Sizing Methods to Cold Climates with Snow Storage Conditions. Water Sci Technol 56(10), 73-81. https://doi.org/10.2166/wst.2007.745

Muthanna, T.M., Viklander, M. and Thorolfsson, S.T. (2008) Seasonal Climatic Effects on the Hydrology of a Rain Garden. Hydrological Processes 22(11), 1640-1649. https://doi.org/10.1002/hyp.6732

National Research Council (2009) Urban Stormwater Management in the United States, The National Academies Press, Washington, DC.

Negm, L.M., Youssef, M.A., Skaggs, R.W., Chescheir, G.M. and Kladivko, E.J. (2014) DRAINMOD-Dssat Simulation of the Hydrology, Nitrogen Dynamics, and Plant Growth of a Drained Corn Field in Indiana. Journal of Irrigation and Drainage Engineering 140(8). https://doi.org/10.1061/(Asce)Ir.1943-4774.0000738

Nemes, A., Pachepsky, Y. and Timlin, D. (2011) Toward Improving Global Estimates of Field Soil Water Capacity. Soil Sci. Soc. Am. J. 75(3), 807-812. https://doi.org/10.2136/sssaj2010.0251

North Carolina Department of Enviromental Quality (2009) Ncdenr Stormwater BMP Manual

Ohio Department of Natural Resources (2006) Rainwater and Land Development: Ohio's Standards for Stormwater Management Land Development and Urban Stream Protection. Ohio Department of Natural Resources, D.o.S.a.W.C. (ed), Columbus, OH.

Olszewski, J.M. and Davis, A.P. (2013) Comparing the Hydrologic Performance of a Bioretention Cell with Predevelopment Values. Journal of Irrigation and Drainage Engineering 139(2), 124-130. https://doi.org/10.1061/(Asce)Ir.1943-4774.0000504

Pachepsky, Y. and Rawls, W.J., (eds) (2004) Development of Pedotransfer Functions in Soil Hydrology, Elsevier Science, Amsterdam.

Palla, A. and Gnecco, I. (2015) Hydrologic Modeling of Low Impact Development Systems at the Urban Catchment Scale. Journal of Hydrology 528, 361-368. https://doi.org/10.1016/j.jhydrol.2015.06.050

Palmer, E.T., Poor, C.J., Hinman, C. and Stark, J.D. (2013) Nitrate and Phosphate Removal through Enhanced Bioretention Media: Mesocosm Study. Water Environment Research 85(9), 823-832. https://doi.org/10.2175/106143013x13736496908997

Papanicolaou, A.N., Elhakeem, M., Wilson, C.G., Burras, C.L., West, L.T., Lin, H., Clark, B. and Oneal, B.E. (2015) Spatial Variability of Saturated Hydraulic Conductivity at the Hillslope Scale: Understanding the Role of Land Management and Erosional Effect. Geoderma 243, 58-68. https://doi.org/10.1016/j.geoderma.2014.12.010

Passeport, E., Hunt, W.F., Line, D.E., Smith, R.A. and Brown, R.A. (2009) Field Study of the Ability of Two Grassed Bioretention Cells to Reduce Storm-Water Runoff Pollution. Journal of Irrigation and Drainage Engineering 135(4), 505-510. https://doi.org/10.1061/(Asce)Ir.1943-4774.0000006

Patil, N.G. and Singh, S.K. (2016) Pedotransfer Functions for Estimating Soil Hydraulic Properties: A Review. Pedosphere 26(4), 417-430. https://doi.org/10.1016/s1002-0160(15)60054-6

Paus, K.H., Morgan, J., Gulliver, J.S., Leiknes, T. and Hozalski, R.M. (2014) Assessment of the Hydraulic and Toxic Metal Removal Capacities of Bioretention Cells after 2 to 8 Years of Service. Water Air and Soil Pollution 225(1). https://doi.org/ARTN 180310.1007/s11270-013-1803-y

Payne, E.G.I., Fletcher, T.D., Russell, D.G., Grace, M.R., Cavagnaro, T.R., Evrard, V., Deletic, A., Hatt, B.E. and Cook, P.L.M. (2014) Temporary Storage or Permanent Removal? The Division of Nitrogen between Biotic Assimilation and Denitrification in Stormwater Biofiltration Systems. PLoS One 9(3). https://doi.org/ARTN e9089010.1371/journal.pone.0090890

Payne, E.G.I., Pham, T., Deletic, A., Hatt, B.E., Cook, P.L.M. and Fletcher, T.D. (2018) Which Species? A Decision-Support Tool to Guide Plant Selection in Stormwater Biofilters. Advances in Water Resources 113, 86-99. https://doi.org/10.1016/j.advwatres.2017.12.022

Pitt, R.E. (1999) Small Storm Hydrology and Why It Is Important for the Design of Stormwater Control Practices. Journal of Water Management Modeling. https://doi.org/10.14796/jwmm.r204-04

Pitt, R.E. and Voorhees, J. (2004) Winslamm and Low Impact Development, College Park, MD.

Rawls, W.J. and Brakensiek, D.L. (1982) Estimating Soil-Water Retention from Soil Properties. Journal of the Irrigation and Drainage Division-Asce 108(2), 166-171. <Go to ISI>://WOS:A1982NS80900007

Rawls, W.J., Brakensiek, D.L. and Miller, N. (1983) Green-Ampt Infiltration Parameters from Soils Data. Journal of Hydraulic Engineering-Asce 109(1), 62-70. https://doi.org/Doi 10.1061/(Asce)0733-9429(1983)109:1(62)

Rawls, W.J., Gimenez, D. and Grossman, R. (1998) Use of Soil Texture, Bulk Density, and Slope of the Water Retention Curve to Predict Saturated Hydraulic Conductivity. Transactions of the Asae 41(4), 983-988. <Go to ISI>://WOS:000075662800010

Ray, C., Bezak, B., Petrey, K. and Shea, E. (2015) Measurement and Optimization of Permeability in Bioretention Soil Media. Lid: It Works in All Climates and Soils, 176-185. <Go to ISI>://WOS:000381031400018

Richards, L.A. and Weaver, L.R. (1944) Moisture Retention by Some Irrigated Soils as Related to Soil Moisture Tension. Journal of Agricultural Research 69, 215-235.

Rosa, D.J., Clausen, J.C. and Dietz, M.E. (2015) Calibration and Verification of SWMM for Low Impact Development. Journal of the American Water Resources Association 51(3), 746-757. https://doi.org/10.1111/jawr.12272

Rossman, L.A. (2010) Modeling Low Impact Development Alternatives with SWMM. Journal of Water Management Modeling. https://doi.org/10.14796/jwmm.r236-11

Rossman, L.A. and Bernagros, J.T. (2018) National Stormwater Calculator User's Guide – Version 1.2.0.1. Division, W.S. and Laboratory, N.R.M.R. (eds), Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH.

Rossman, L.A. and Huber, W.C. (2016a) Storm Water Management Model Reference Manual Volume Iii – Water Quality. Division, O.o.R.a.D.W.S.a.W.R. (ed), National Risk Management Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cinncinati, OH.

Rossman, L.A. and Huber, W.C. (2016b) Storm Water Management Model Reference Manual: Volume I – Hydrology (Revised). Division, O.o.R.a.D.W.S.a.W.R. (ed), National Risk Management Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH.

Roy-Poirier, A., Champagne, P. and Filion, Y. (2010) Review of Bioretention System Research and Design: Past, Present, and Future. Journal of Environmental Engineering 136(9), 878-889. https://doi.org/10.1061/(Asce)Ee.1943-7870.0000227

Roy-Poirier, A., Filion, Y. and Champagne, P. (2015) An Event-Based Hydrologic Simulation Model for Bioretention Systems. Water Sci Technol 72(9), 1524-1533. https://doi.org/10.2166/wst.2015.368

Salazar, O., Wesstrom, I. and Joel, A. (2008) Evaluation of DRAINMOD Using Saturated Hydraulic Conductivity Estimated by a Pedotransfer Function Model. Agricultural Water Management 95(10), 1135-1143. https://doi.org/10.1016/j.agwat.2008.04.011

Saraswat, D., Frankenberg, J.R., Pai, N., Ale, S., Daggupati, P., Douglas-Mankin, K.R. and Youssef, M.A. (2015) Hydrologic and Water Quality Models: Documentation and Reporting Procedures for Calibration, Validation, and Use. Transactions of the ASABE 58(6), 1787-1797. <Go to ISI>://WOS:000368341900025

Saxton, K.E. and Rawls, W.J. (2006) Soil Water Characteristic Estimates by Texture and Organic Matter for Hydrologic Solutions. Soil Science Society of America Journal 70(5), 1569. https://doi.org/10.2136/sssaj2005.0117

Saxton, K.E., Rawls, W.J., Romberger, J.S. and Papendick, R.I. (1986) Estimating Generalized Soil-Water Characteristics from Texture. Soil Science Society of America Journal 50(4), 1031-1036. https://doi.org/DOI 10.2136/sssaj1986.03615995005000040039x

Schaap, M.G. and Leij, F.J. (1998) Using Neural Networks to Predict Soil Water Retention and Soil Hydraulic Conductivity. Soil & Tillage Research 47(1-2), 37-42. https://doi.org/Doi 10.1016/S0167-1987(98)00070-1

Schaap, M.G., Leij, F.J. and van Genuchten, M.T. (2001) Rosetta: A Computer Program for Estimating Soil Hydraulic Parameters with Hierarchical Pedotransfer Functions. Journal of Hydrology 251(3-4), 163-176. https://doi.org/Doi 10.1016/S0022-1694(01)00466-8

Šejna, M., Šimůnek, J. and van Genuchten, M.T. (2014) HYDRUS User Manual: Version 2.04, PC-Progress, Prague, Czech Republic.

Seo, M., Jaber, F., Srinivasan, R. and Jeong, J. (2017) Evaluating the Impact of Low Impact Development (LID) Practices on Water Quantity and Quality under Different Development Designs Using SWAT. Water 9(3), 193. https://doi.org/10.3390/w9030193

Shoemaker, L., Riverson, J.J., Alvi, K., Zhen, J.X. and Murphy, R. (2011) Report on Enhanced Framework (SUSTAIN) and Field Applications for Placement of BMPs in Urban Watersheds. Office of Research and Development, N.R.M.R.L.-W.S.a.W.R.D. (ed), National Risk Management Research Laboratory, Office of Research and Development, Cincinnati, OH.

Shoemaker, L., Riverson, J.J., Alvi, K., Zhen, J.X., Murphy, R. and Wood, B. (2013) Stormwater Management for Tmdls in an Arid Climate: A Case Study Application of SUSTAIN in Albuquerque, New Mexico. Development, O.o.R.a. (ed), National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH.

Shoemaker, L., Riverson, J.J., Alvi, K., Zhen, J.X., Paul, S. and Rafi, T. (2009) SUSTAIN - a Framework for Placement of Best Management Practices in Urban Watersheds to Protect Water Quality Report. Development, O.o.R.a. and Division, N.R.M.R.L.-W.S.a.W.R. (eds), National Risk Management Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH.

Sivapalan, M. and Young, P.C. (2006) Downward Approach to Hydrological Model Development. Encyclopedia of hydrological sciences.

Skaggs, R.W. (1980) DRAINMOD Reference Report, USDA-SCS South National Technical Center, Fort Worth, TX.

Skaggs, R.W. (1991) Modeling Plant and Soil Systems. Hanks, J. and Ritchie, J. (eds), pp. 205-243, ASA, Madison, WI.

Skaggs, R.W., Youssef, M.A. and Chescheir, G.M. (2012) DRAINMOD: Model Use, Calibration, and Validation. Transactions of the ASABE 55(4), 1509-1522. <Go to ISI>://WOS:000309089900030

Stander, E.K. and Borst, M. (2010) Hydraulic Test of a Bioretention Media Carbon Amendment. Journal of Hydrologic Engineering 15(6), 531-536. https://doi.org/10.1061/(Asce)He.1943-5584.0000133

Stewart, R.D., Lee, J.G., Shuster, W.D. and Darner, R.A. (2017) Modelling Hydrological Response to a Fully-Monitored Urban Bioretention Cell. Hydrological Processes 31(26), 4626-4638. https://doi.org/10.1002/hyp.11386

Sun, Y.-w., Li, Q.-y., Liu, L., Xu, C.-d. and Liu, Z.-p. (2014) Hydrological Simulation Approaches for BMPs and LID Practices in Highly Urbanized Area and Development of Hydrological Performance Indicator System. Water Science and Engineering 7(2), 143-154. https://doi.org/10.3882/j.issn.1674-2370.2014.02.003

Sun, Y.-w., Wei, X.-m.C. and Pomeroy, C.A. (2011) Global Analysis of Sensitivity of Bioretention Cell Design Elements to Hydrologic Performance. Water Science and Engineering, 4(3), 246-257. https://doi.org/10.3882/j.issn.1674-2370.2011.03.002

Thornthwaite, C.W. (1948) An Approach toward a Rational Classification of Climate. Geographical Rev. 38(1), 55-94.

Tian, F., Sun, Y., Hu, H. and Li, H. (2016) Searching for an Optimized Single-Objective Function Matching Multiple Objectives with Automatic Calibration of Hydrological Models. Hydrology and Earth System Sciences Discussions, 1-33. https://doi.org/10.5194/hess-2016-88

Tiveron, T., Gholamreza-Kashi, S. and Joksimovic, D. (2018) A Usepa SWMM Integrated Tool for Determining the Suspended Solids Reduction Performance of Bioretention Cells. Journal of Water Management Modeling 26. https://doi.org/Artn C44310.14796/Jwmm.C443

Turney, I.D. and Neilson, B. (2010) Ultra Urban Green Street Design Criteria. Struck, S. and Lichten, K. (eds), pp. 642-660, American Society of Civil Engineers, San Francisco, CA.

U.S. Army Corps of Engineers (2018) Hydrologic Modeling System HEC-HMS User's Manual. Hydrologic Engineering Center and Institute for Water Resources (eds), Davis, CA.

U.S. EPA (2017) National Water Quality Inventory: Report to Congress Water, O.o. (ed), U.S. Environmental Protection Agency, Washington DC.

van Genuchten, M.T. (1980) A Closed-Form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. Soil Science Society of America Journal 44, 892-898.

van Genuchten, M.T. (1985) Convective-Dispersive Transport of Solutes Involved in Sequential First-Order Decay Reactions. Computers & Geosciences 11(2), 129-147.

van Schilfgaarde, J. (1974) Drainage for Agriculture. van Schilfgaarde, J. (ed), pp. 245-270, American Society of Agronomy, Madison, WI.

Wadzuk, B.M., Hickman, J.M. and Traver, R.G. (2015) Understanding the Role of Evapotranspiration in Bioretention: Mesocosm Study. Journal of Sustainable Water in the Built Environment 1(2). https://doi.org/Artn 0401400210.1061/Jswbay.0000794

Wan, Z.X., Li, T. and Liu, Y.T. (2018) Effective Nitrogen Removal During Different Periods of a Field-Scale Bioretention System. Environmental Science and Pollution Research 25(18), 17855-17861. https://doi.org/10.1007/s11356-018-1954-x

Wang, J., Chua, L.H.C. and Shanahan, P. (2017) Evaluation of Pollutant Removal Efficiency of a Bioretention Basin and Implications for Stormwater Management in Tropical Cities. Environmental Science-Water Research & Technology 3(1), 78-91. https://doi.org/10.1039/c6ew00285d

Wang, M., Zhang, D.Q., Li, Y., Hou, Q.H., Yu, Y.Y., Qi, J.D., Fu, W.C., Dong, J.W. and Cheng, Y.N. (2018) Effect of a Submerged Zone and Carbon Source on Nutrient and Metal Removal for Stormwater by Bioretention Cells. Water 10(11). https://doi.org/ARTN 162910.3390/w10111629

Warrick, A.W. and Nielsen, D.R. (1980) Applications of Soil Physics. Hill, D. (ed), pp. 319–344, Academic Press, Inc., New York.

Water Balance Model Powered by Qualhymo: Technical Manual (2019), The Partnership for Water Sustainability.

Wilson, C.E., Hunt, W.F., Winston, R.J. and Smith, P. (2015) Comparison of Runoff Quality and Quantity from a Commercial Low-Impact and Conventional Development in Raleigh, North Carolina. Journal of Environmental Engineering 141(2), 05014005. https://doi.org/doi:10.1061/(ASCE)EE.1943-7870.0000842

Winston, R.J. (2015) Resilience of Green Infrastructure under Extreme Conditions. Doctoral dissertation.

Winston, R.J., Dorsey, J.D. and Hunt, W.F. (2016) Quantifying Volume Reduction and Peak Flow Mitigation for Three Bioretention Cells in Clay Soils in Northeast Ohio. Sci Total Environ 553, 83-95. https://doi.org/10.1016/j.scitotenv.2016.02.081

Wong, T.H.F., Fletcher, T.D., Duncan, H.P., Coleman, J.R. and Jenkins, G.A. (2002) A Model for Urban Stormwater Improvement Conceptualisation, pp. 48-53, American Society of Civil Engineers, Portland, Oregon.

Wong, T.H.F., Fletcher, T.D., Duncan, H.P. and Jenkins, G.A. (2006) Modelling Urban Stormwater Treatment—a Unified Approach. Ecological Engineering 27(1), 58-70. https://doi.org/10.1016/j.ecoleng.2005.10.014

Wosten, J.H.M., Finke, P.A. and Jansen, M.J.W. (1995) Comparison of Class and Continuous Pedotransfer Functions to Generate Soil Hydraulic Characteristics. Geoderma 66(3-4), 227-237. https://doi.org/Doi 10.1016/0016-7061(94)00079-P

Wosten, J.H.M., Pachepsky, Y.A. and Rawls, W.J. (2001) Pedotransfer Functions: Bridging the Gap between Available Basic Soil Data and Missing Soil Hydraulic Characteristics. Journal of Hydrology 251(3-4), 123-150. https://doi.org/Doi 10.1016/S0022-1694(01)00464-4

Wright, O.M., Istanbulluoglu, E., Horner, R.R., DeGasperi, C.L. and Simmonds, J. (2018) Is There a Limit to Bioretention Effectiveness? Evaluation of Stormwater Bioretention Treatment Using a Lumped Urban Ecohydrologic Model and Ecologically Based Design Criteria. Hydrological Processes 32(15), 2318-2334. https://doi.org/10.1002/hyp.13142

Xie, J., Chenab, H., Liao, Z., Gua, X., Zhu, D. and Zhang, J. (2017) An Integrated Assessment of Urban Flooding Mitigation Strategies for Robust Decision Making. Environmental Modelling & Software 95, 143-155. https://doi.org/https://doi.org/10.1016/j.envsoft.2017.06.027

Yang, X.H., Mei, Y., He, J., Jiang, R., Li, Y.Q. and Li, J.Q. (2014) Comprehensive Assessment for Removing Multiple Pollutants by Plants in Bioretention Systems. Chinese Science Bulletin 59(13), 1446-1453. https://doi.org/10.1007/s11434-014-0200-2
Yang, Y. and Chui, T.F.M. (2018) Optimizing Surface and Contributing Areas of Bioretention Cells for Stormwater Runoff Quality and Quantity Management. J Environ Manage 206, 1090-1103. https://doi.org/10.1016/j.jenvman.2017.11.064
Youssef, M.A., Abdelbaki, A.M., Negm, L.M., Skaggs, R.W., Thorp, K.R. and Jaynes, D.B. (2018) DRAINMOD-Simulated Performance of Controlled Drainage across the Us Midwest. Agricultural Water Management 197, 54-66.
Youssef, M.A., Skaggs, R.W., Chescheir, G.M. and Gilliam, J.W. (2005) The Nitrogen Simulation Model, DRAINMOD-N Ii. Transactions of the Asae 48(2), 611-626. <Go to ISI>://WOS:000229031800018
Zhang, G., Hamlett, J.M. and Saravanapavan, T. (2010) Representation of Low Impact Development Scenarios in SWMM. Journal of Water Management Modeling. https://doi.org/10.14796/jwmm.r236-12
Zhang, K. and Chui, T.F.M. (2017) Evaluating Hydrologic Performance of Bioretention Cells in Shallow Groundwater. Hydrological Processes 31(23), 4122-4135. https://doi.org/10.1002/hyp.11308
Zhang, K. and Chui, T.F.M. (2018) Interactions between Shallow Groundwater and Low-Impact Development Underdrain Flow at Different Temporal Scales. Hydrological Processes 32(23), 3495-3512. https://doi.org/10.1002/hyp.13272
Zhang, K., Chui, T.F.M. and Yang, Y. (2018a) Simulating the Hydrological Performance of Low Impact Development in Shallow Groundwater Via a Modified SWMM. Journal of Hydrology 566, 313-331. https://doi.org/10.1016/j.jhydrol.2018.09.006
Zhang, L., Lu, Q., Ding, Y., Peng, P. and Yao, Y. (2018b) Design and Performance Simulation of Road Bioretention Media for Sponge Cities. J. Perform. Constr. Facil. 32(5). https://doi.org/10.1061/(ASCE)CF.1943-5509.0001209.©2018
Zhang, S. and Guo, Y. (2013) Stormwater Capture Efficiency of Bioretention Systems. Water Resources Management 28(1), 149-168. https://doi.org/10.1007/s11269-013-0477-y

APPENDICES

Appendix A- How to use DRAINMOD-Urban for bioretention cell modeling

A-1 Installation and setup of DRAINMOD-Urban

First, the original DRAINMOD program must be downloaded from: https://www.bae.ncsu.edu/agricultural-water-management/drainmod/download/

The DRAINMOD version used in this study was v. 6.1 Build 105 released in April 2013. Following download and installation, the DRAINMOD executable and sample input files can be found in the C:// drive (Be careful during installation to change the location to the main C:// drive. The default often suggests the installation location under "program files" in the C:// drive but that is harder to use for DRAINMOD-Urban). The executable files in the download can be found in Figure A-1 and the sample input files can be found in the inputs, soil, and weather folders. Model documentation and help files for the original DRAINMOD can be found here: https://www.bae.ncsu.edu/agricultural-water-management/drainmod/manuals/

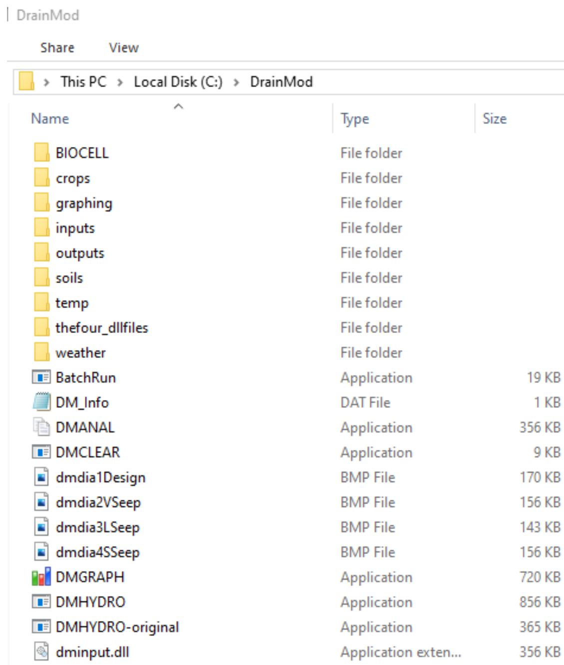


Figure A-1. Default input files downloaded to C:// drive with DRAINMOD installation. The BIOCELL folder was created for DRAINMOD-Urban inputs (INFLOW and RAIN_BIO) and outputs (BIORET).

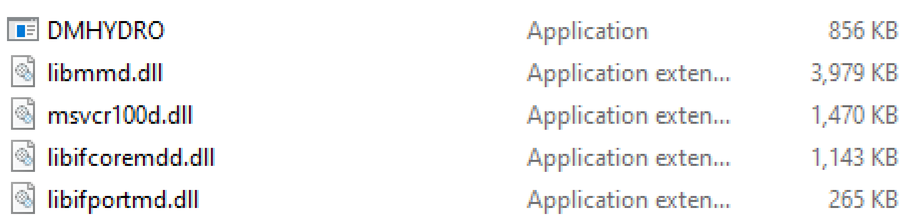


Figure A-2. Additional files must be added to the main C://DrainMod folder to convert to DRAINMOD-Urban.

To convert DRAINMOD to DRAINMOD-Urban, the following steps must be taken. Four new .dll extension files and a new DMHYDRO.exe file must be added to the DrainMod folder on the C:// drive. The .dll files are labeled: libifcoremdd.dll, libifportmd.dll, libmmd.dll and msvcr100d.dll (Figure A-2). The new DMHYDRO.exe file must replace the old DMHYDRO.exe file. However, it is recommended that the old DMHYDRO.exe file be renamed "DMHYDRO-original" or similar so that it is available in the future if the user wishes to use the original DRAINMOD (Figure A-1). These files can be requested from the author and will be available through North Carolina State University in the future.

A folder for DRAINMOD-Urban inputs and outputs must be created labeled "BIOCELL". Inside the BIOCELL folder must be two additional input files: one for the inflow to the bioretention cell (INFLOW.inp) and one for the sub-hourly rainfall (RAIN_BIO.inp). More information on the formatting of these files can be found in section A-3 below. The folder and file labels are important as that is how DRAINMOD knows where to look for the additional inputs. Therefore, no additional label can be added to these files (such as "INFLOW-UC cell.inp") or else the program will not run. It is suggested that to keep inputs organized, additional labels be used as .txt files. When ready to use in DRAINMOD-Urban, the text files can be saved as the INFLOW.inp (or RAIN_BIO.inp) file. Also, ".inp" is simply the file extension but should not be included in the file name. Therefore, the inflow file should be saved as "INFLOW.inp" and saved as "All Files". Then the file name should appear as "INFLOW" with ".inp" as the file extension.

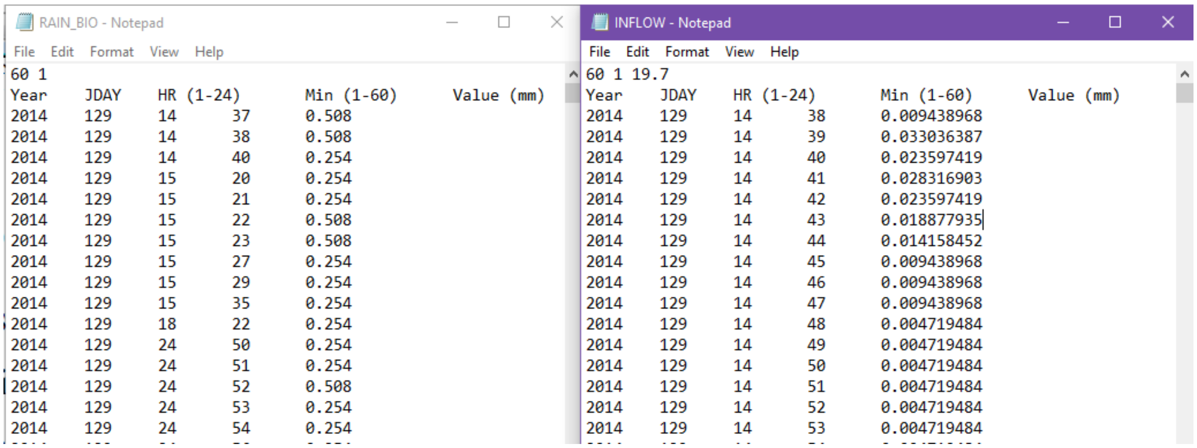
A-2 Inflow Inputs for DRAINMOD-Urban

DRAINMOD-Urban was modified so that inflow can be easily input into the model and added to the total precipitation entering a bioretention cell. The precipitation and inflow files are entered as separate text files formatted as shown in Figure A-3 and described below. The Precipitation file must be called “RAIN_BIO” and the inflow file is called “INFLOW”. These files must be saved as input (.inp) files in a folder called “BIOCELL” in the same file location as the DRAINMOD executable file and the other input and output file folders (Figure A-4).

The RAIN_BIO file starts with two numbers on line 1 which describe the number of time increments in an hour and the time step in minutes (60 and 1 respectively for 1-minute data). Similarly, for 15-minute data the first two numbers would be 4 and 15, respectively. The next line contains the column headings (Year, JDay, Hr, Min, and Value). JDay stands for Julian day within the given year (1-365, 366 for leap years). The hour and minute are listed in the next two columns, but to avoid using zeros, these must be labeled from 1-24 and 1-60 respectively. Finally, the value of the precipitation for that given time step is reported in mm.

The INFLOW file begins with the same two numbers as the RAIN_BIO file (the number of time increments in an hour and the time step in minutes). It also includes the field ratio described above as the contributing area over the bioretention area (in this example, 19.7). The next line contains the column headers which are the same as the RAIN_BIO file except this time the value corresponds to the measured inflow for a given time step reported in mm. **Note:** the time steps included are not identical for the two text files because zero values are not included.

If these methods are followed, DRAINMOD-Urban will incorporate the inflow from the contributing catchment without the use of the “Contributing Area Runoff” function (which must NOT be checked in Project Settings when using DRAINMOD-Urban).



RAIN_BIO - Notepad

```
60 1
Year	JDAY	HR (1-24)	Min (1-60)	Value (mm)
2014	129	14	37	0.508
2014	129	14	38	0.508
2014	129	14	40	0.254
2014	129	15	20	0.254
2014	129	15	21	0.254
2014	129	15	22	0.508
2014	129	15	23	0.508
2014	129	15	27	0.254
2014	129	15	29	0.254
2014	129	15	35	0.254
2014	129	18	22	0.254
2014	129	24	50	0.254
2014	129	24	51	0.254
2014	129	24	52	0.508
2014	129	24	53	0.254
2014	129	24	54	0.254
```

INFLOW - Notepad

```
60 1 19.7
Year	JDAY	HR (1-24)	Min (1-60)	Value (mm)
2014	129	14	38	0.009438968
2014	129	14	39	0.033036387
2014	129	14	40	0.023597419
2014	129	14	41	0.028316903
2014	129	14	42	0.023597419
2014	129	14	43	0.018877935
2014	129	14	44	0.014158452
2014	129	14	45	0.009438968
2014	129	14	46	0.009438968
2014	129	14	47	0.009438968
2014	129	14	48	0.004719484
2014	129	14	49	0.004719484
2014	129	14	50	0.004719484
2014	129	14	51	0.004719484
2014	129	14	52	0.004719484
2014	129	14	53	0.004719484
```

Figure A-3. The RAIN_BIO file (left) starts with two numbers on line 1 which describe the number of time increments in an hour and the time step in minutes. The next line contains the column headings. Similarly, the INFLOW file (right) starts with the same two numbers as the RAIN_BIO file plus the field ratio (19.7). The next line contains the column headings for the inflow.

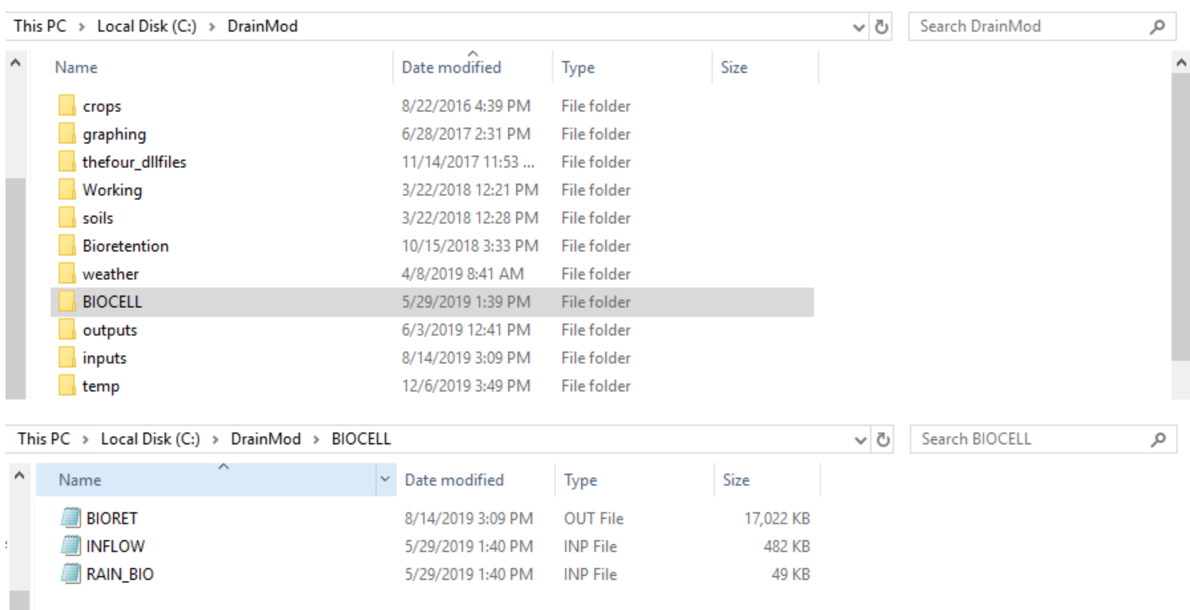


Figure A-4. The top image shows the location of the executable file in the DRAINMOD folder on the C:/ drive. There are automatically input and output files for DRAINMOD in this folder and another folder named BIOCELL has been added. In the BIOCELL folder (bottom image), the INFLOW and RAIN_BIO text files are saved as .inp files.

A-3 Contributing Area Runoff Function in DRAINMOD

For comparison to the above, a description of how inflow was processed in the original DRAINMOD is included in this section. The "Contributing Area Runoff" function has been used in previous studies that modeled bioretention in DRAINMOD (Winston, 2015; Brown et al., 2013). This is a method of determining surface runoff from the contributing drainage area which is added to the precipitation as an inflow to a bioretention system. Step by step instructions on how to apply this method for bioretention has been described by Brown (2011) in the Appendix A: User's Manual for Modeling Bioretention with DRAINMOD.

First, the precipitation and other weather inputs for the specified location are entered into DRAINMOD. The Green-Ampt parameters and system design are adjusted in DRAINMOD to represent a typical parking lot as a contributing area. DRAINMOD is run with the "Hourly Surface Runoff" box (Figure A-5) checked to create a .SRO runoff file. The output file from this simulation can be compared and calibrated against measured data by adjusting the maximum surface storage in the drainage design inputs.

In the "Contributing Area Runoff" utility, information about the contributing catchment like the contributing area (ha), the time of concentration (hrs) and the instantaneous unit hydrograph (IUH) adjustment factor is entered into the model and the .SRO file that was just created is entered into the utility interface as seen in Figure A-6. By clicking "create" in this interface, an overland flow (.OVR) file for the contributing area will be created.

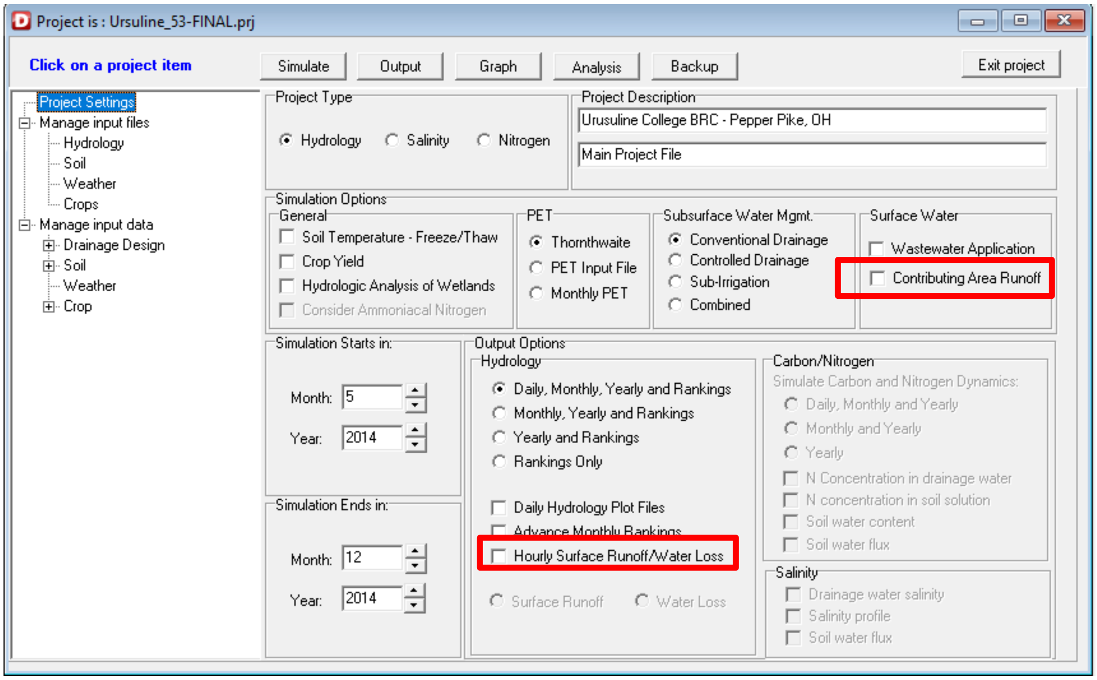


Figure A-5. The initial interface of DRAINMOD that describes project settings. To create the .SRO file the "Hourly Surface Runoff" box must be checked. To include the .OVR overland flow file in the inflow of the model, the "Contributing Area Runoff" box must be checked.

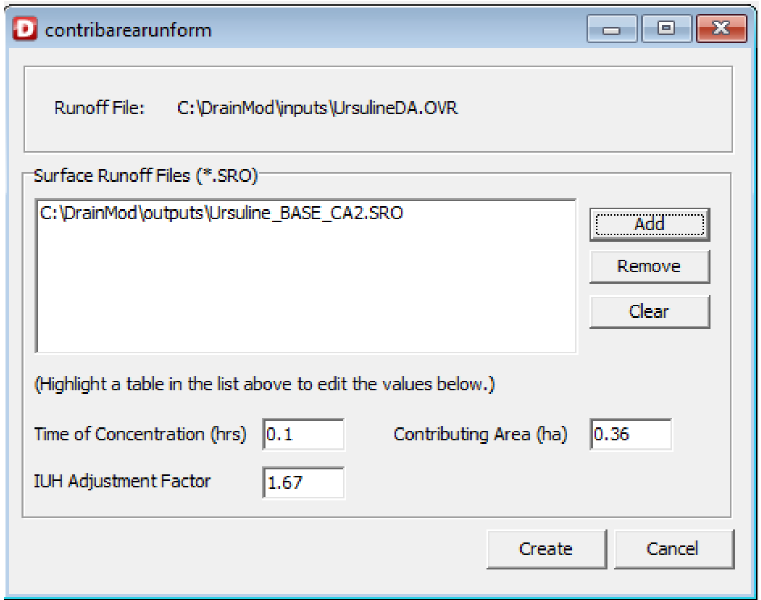


Figure A-6. User interface for the Contributing Area Runoff function in DRAINMOD. The time of concentration and instantaneous unit hydrograph (IUH) adjustment factor used in this example is typical for a standard parking lot.

Next, DRAINMOD is setup to represent the bioretention cell by adjusting the drainage design and soil parameters, and crop parameters if applicable. The "Contributing Area Runoff" checkbox must be checked in the Project Settings (Figure A-5) to include the runoff from the previously modeled parking lot in the inflow reaching the bioretention cell.

Under the "Hydrology" tab of the "Manage input files" menu is a section for the "Contributing Area Runoff" function (Figure A-7). Here the correct .OVR overland flow file will be uploaded and the appropriate field ratio will be added. The field ratio can be calculated as the drainage area over the bioretention area.

If these methods are followed, DRAINMOD will incorporate the inflow from the contributing catchment using the “Contributing Area Runoff” function. However, this method is cumbersome and requires calibration of the contributing runoff to measured inflow.

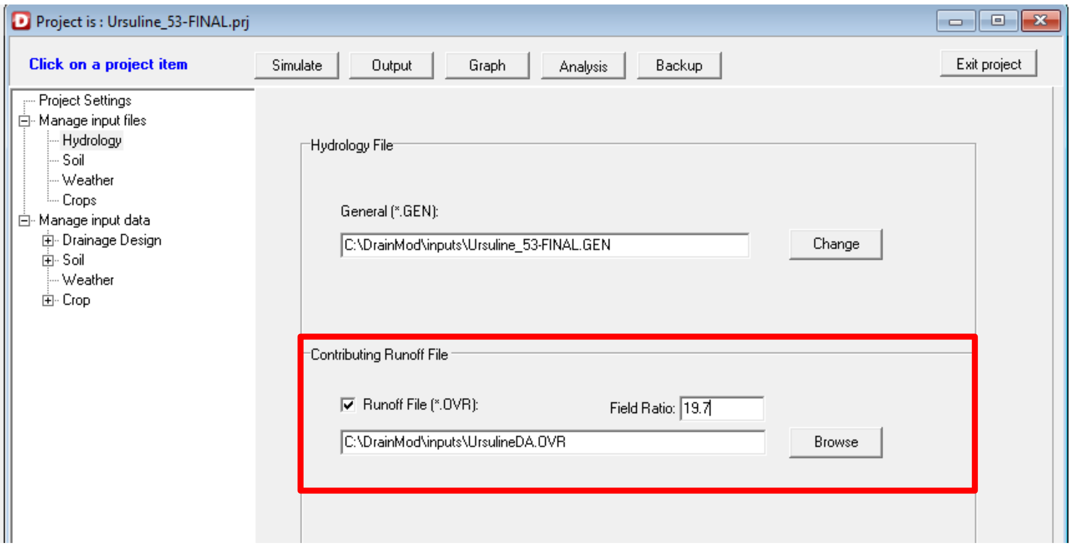


Figure A-7. The User interface for uploading the Contributing Area Runoff .OVR file. This is required to include inflow in this simulation. The field ratio is the contributing area over the bioretention area.

A-4 How to set-up and run a DRAINMOD-Urban simulation

To run DRAINMOD-Urban, DRAINMOD application is opened and set up in the same way as the traditional DRAINMOD. The project settings are selected to create the .GEN file (Figure A-8). For bioretention systems with an internal water storage (IWS) zone, the “Controlled Drainage” option under “Subsurface Water Mgmt.” should be selected. For a bioretention cell without an IWS zone, “Conventional Drainage” is appropriate. When using

DRAINMOD-Urban, it is important that the “Contributing Area Runoff” box be left unchecked. This is because the user-supplied inflow file in DRAINMOD-Urban replaces the “Contributing Area Runoff” utility in DRAINMOD. More information on the differences between these two functions can be found in sections A-2 and A-3 above.

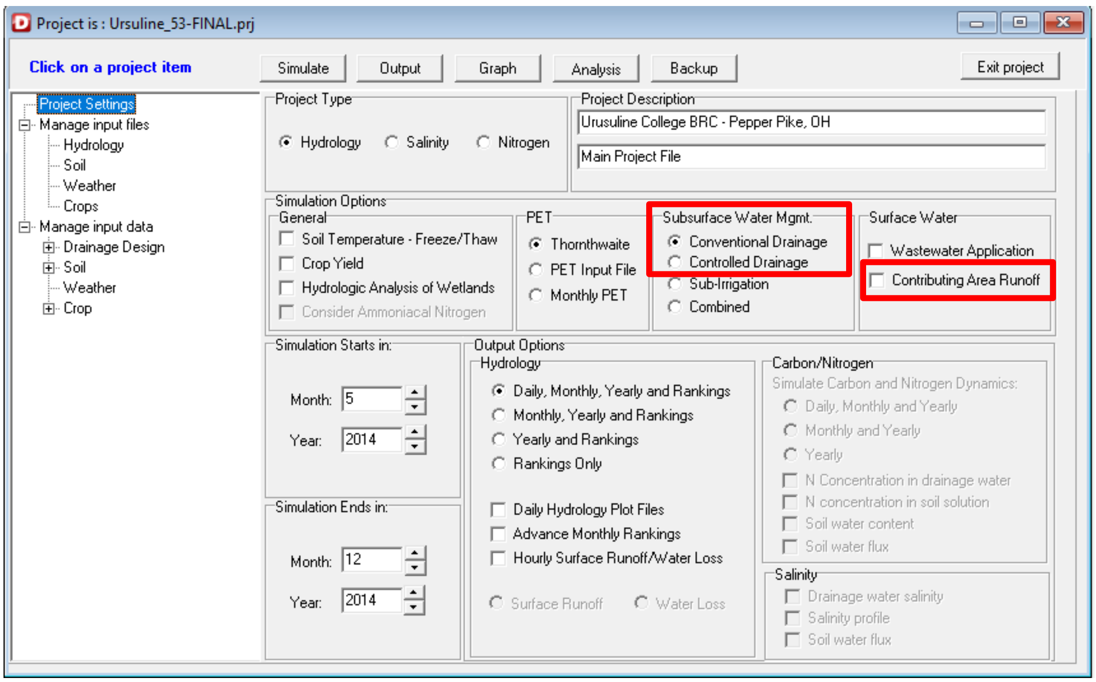
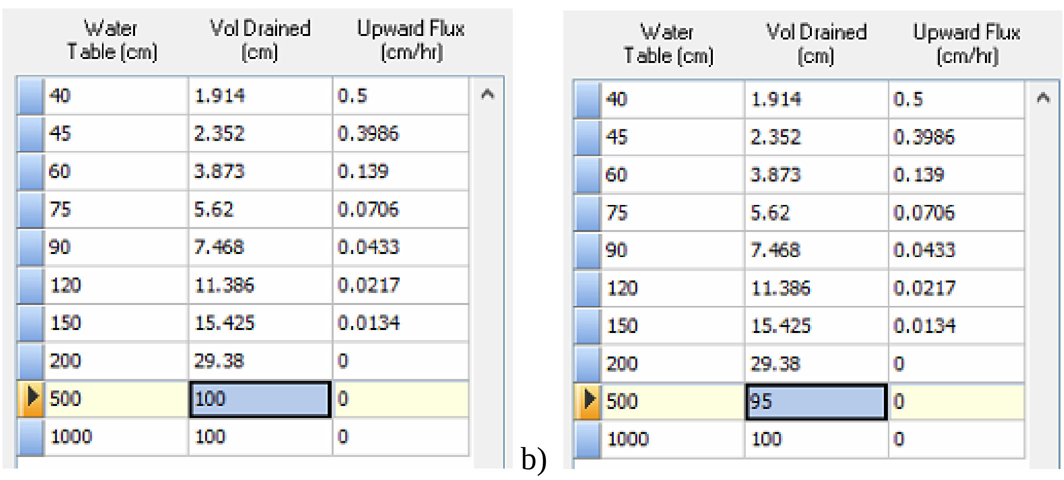


Figure A-8. Project Settings page in the DRAINMOD graphical user interface (GUI). The Subsurface Water Mgmt. options are important to the drainage configuration of the bioretention cell. The Contributing Area Runoff box must be unchecked for a DRAINMOD-Urban simulation.

The soil file can be created with the “Create Soil File” utility built in to DRAINMOD. **Note:** A bug was found in the soil file that prevents DRAINMOD-Urban from running. Sometimes when using the “Create Soil File” utility the volume drained versus water table depth can show duplicate volumes as the drainage levels out at the end of the file (100 cm drained for both 500 and 1000 cm water table depth in Figure A-9a). If this occurs, simply change the second to last value to be slightly smaller (such as 95) and the program will run (Figure A-9b). The weather files (Rainfall and Temperature) can also be created in the “Create Weather File” utility in DRAINMOD. **Note:** this is the hourly rainfall and daily temperature required by the original DRAINMOD which is required in addition to the sub-hourly rainfall in the RAIN_BIO.inp file.



a)

Water Table (cm)	Vol Drained (cm)	Upward Flux (cm/hr)
40	1.914	0.5
45	2.352	0.3986
60	3.873	0.139
75	5.62	0.0706
90	7.468	0.0433
120	11.386	0.0217
150	15.425	0.0134
200	29.38	0
500	100	0
1000	100	0

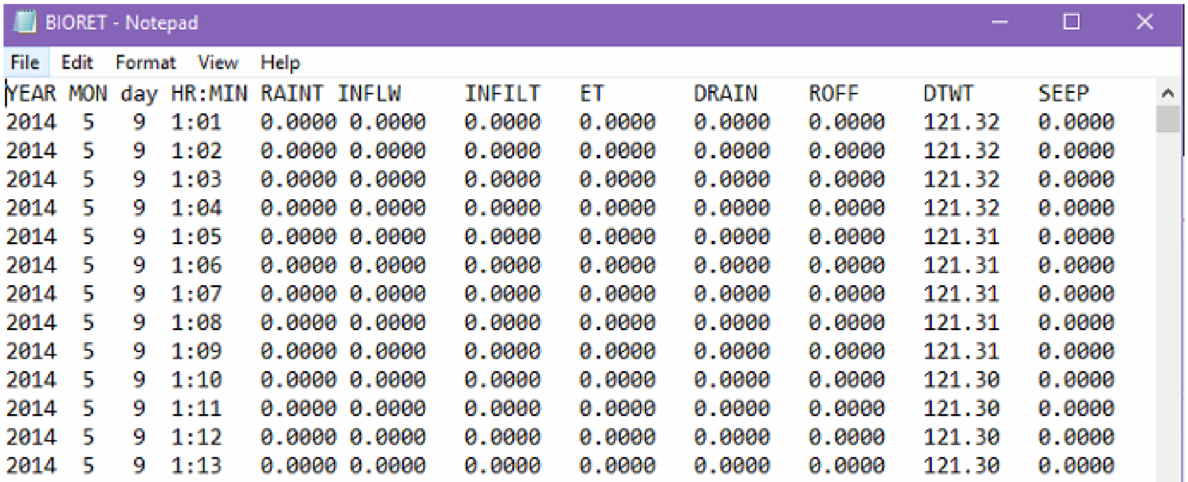
b)

Water Table (cm)	Vol Drained (cm)	Upward Flux (cm/hr)
40	1.914	0.5
45	2.352	0.3986
60	3.873	0.139
75	5.62	0.0706
90	7.468	0.0433
120	11.386	0.0217
150	15.425	0.0134
200	29.38	0
500	95	0
1000	100	0

Figure A-9. The water table depth versus volume drained can cause a bug in DRAINMOD-Urban if the last two volumes are identical (a). It is suggested to reduce the second to last volume slightly (b).

When all the input files are uploaded and the drainage design, soil, weather and crop parameters are entered through the graphical user interface (GUI), then the “Simulate” button can be used to create model outputs. The outputs provided by the original DRAINMOD (Day, Month, Year, and Rank files) are still created and stored in the “outputs” folder in the C:// drive.

Another sub-hourly output file is created called “BIORET.out” and stored in the BIOCELL folder (Figure A-4). This file will be overwritten by any successive model simulations. The columns of the BIORET output file are described as follows (Figure A-10). YEAR, MON and day make up the date and HR:MIN the time of the output. Here the hour and min are still adjusted from the input file to run from 1 to 24 hours and 1 to 60 minutes. Therefore, when post-processing the output data, the first timestep 1:01 corresponds to midnight (0:00). Units for all the following columns is in cm per bioretention area (cm/BRA). The RAINT column stands for Rain Total which is equal to the total rainfall and inflow entering the bioretention cell in cm/BRA. The inflow entered in the INFLOW.inp file is reprinted in the next column (INFLW) in cm/BRA to be able to separate rainfall and inflow if desired. INFILT is the total infiltration into the bioretention cell. ET is the evapotranspiration at each timestep. DRAIN stands for drainage from the underdrain below the bioretention cell. ROFF stands for runoff from the surface storage of the bioretention cell (also known as overflow). DTWT represents the depth to the water table starting from the soil surface. SEEP is the seepage (or exfiltration) underneath the bioretention cell into the surrounding soil.



YEAR	MON	day	HR:MIN	RAINT	INFLW	INFILT	ET	DRAIN	ROFF	DTWT	SEEP
2014	5	9	1:01	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	121.32	0.0000
2014	5	9	1:02	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	121.32	0.0000
2014	5	9	1:03	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	121.32	0.0000
2014	5	9	1:04	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	121.32	0.0000
2014	5	9	1:05	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	121.31	0.0000
2014	5	9	1:06	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	121.31	0.0000
2014	5	9	1:07	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	121.31	0.0000
2014	5	9	1:08	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	121.31	0.0000
2014	5	9	1:09	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	121.31	0.0000
2014	5	9	1:10	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	121.30	0.0000
2014	5	9	1:11	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	121.30	0.0000
2014	5	9	1:12	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	121.30	0.0000
2014	5	9	1:13	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	121.30	0.0000

Figure A-10. An example of the BIORET.out file. The columns represent YEAR, MON, day=date, HR:MIN=time minus one hour and one minute (1:01=0:00), RAINT=inflow + rainfall, INFLW=inflow, INFILT=infiltration, ET=evapotranspiration, DRAIN=drainage, ROFF=overflow, DTWT=depth to water table, SEEP=seepage. All units are in cm per bioretention area (cm/BRA).

A-5 Post-processing of DRAINMOD-Urban output

As you can imagine, simulations at a minute-scale provide a wealth of data that must be processed. To ease this process for this dissertation and for future DRAINMOD-Urban users, a macro-enabled spreadsheet was creating using excel VBA. This spreadsheet can be requested from the author and is expected to be available through North Carolina State University in the future. Steps to use the spreadsheet are included below; however, significant changes in the spreadsheet may take place over time. Therefore, for the most updated information, please refer to documentation from North Carolina State University.

The first step is to fill out the site information on the first worksheet “Instructions & Site Info”. This is used for documentation mostly but the bioretention area and drainage area (m^2) is required which is used in later sub-routines. Only type in the orange input boxes (the areas in ft^2

should be calculated automatically). Two buttons are next to the Site Information to clear data. The "Clear All" button clears all data calculated or input to the spreadsheet while keeping the worksheets and labels on each sheet. The "Clear All But Measured Data" is used to clear all calculated data from a spreadsheet but leave the measured data so that it can be compared to another DRAINMOD-Urban simulation. If no measured data has been added to the spreadsheet yet, simply copy measured drainage and overflow in cm/BRA (must be a continuous file with observed zero values) and paste into the worksheet labeled "Measured Data" under columns B and C respectively with the date and time listed in column A. Next, copy and paste raw data from the BIORET file output by DRAINMOD-Urban to the "DM-BR Raw Data" worksheet. This spreadsheet tool runs through many sequential sub-routines as follows:

"Organized Data": This sub-routine combines the date and time into a single column while adjusting the time back to its original state (minus one hour and one minute). It also hides columns that were irrelevant to this study, but this can be changed to each user's application by adjusting the VBA code "Hidden" from True to False for selected columns.

"Find Measured Events": This sub-routine scans the measured data to find drainage and overflow events. Events are programmed to be separated by 7 hours. This sub-routine outputs the start date, stop date, starting and stopping cell (referencing the "Measured Data" worksheet) for both drainage and overflow events in the "Event Data" worksheet. The data calculated for the "Event Data" worksheet will remain in place if "Clear All But Measured Data" is used. Therefore, "Find Measured Events" only needs to be used when new data is pasted into the "Measured Data" worksheet.

“Find DRAINMOD Events”: Similar to the “Find Measured Events” sub-routine, this sub-routine scans the DRAINMOD-Urban data in the “Organized Data” worksheet to find drainage and overflow events. Events are programmed to be separated by 7 hours. This sub-routine outputs the start date, stop date, starting and stopping cell (referencing the “Organized Data” worksheet) for both drainage and overflow events in the “Event Data” worksheet.

After completing the “Find DRAINMOD Events” sub-routine, it is imperative that a manual step be taken to check that the measured and modeled events match. This is a good check on the programming. The user must go to the “Event Data” worksheet and enter corresponding numbers for drainage and overflow events that match measured dates. For example, a measured drainage event #1 may have a start date of “6/18/14 18:02”. The DRAINMOD-Urban drainage event that has the closest start date is event #5 at “6/18/14 17:50”. Therefore, under the “Event Numbers” heading in the “DM Drainage #” column, 5 is entered in the same row as measured event #1 (row 10). This continues for all measured drainage events compared to measured overflow events (Overflow #), modeled drainage events (DM Drainage #) and modeled overflow events (DM Overflow #). This process is imperative to make sure that events at the same day and time are compared to each other. If an event is to be left out of the analysis, such as an error in the measured data, then the matching Event Number can be left blank. Next, the following sub-routines are completed in order.

“Create Sheets”: This sub-routine creates a new worksheet for each measured drainage event with the headings associated with the “Example Sheet” worksheet. The measured and modeled drainage and overflow is copied to its corresponding sheet for each date with a measured drainage event.

“Statistics”: This sub-routine calculates the numerator and denominator of the Nash-Sutcliffe Efficiency (NSE) and the measured minus simulated error at each time step to calculate the NSE and percent bias (PBIAS) for each drainage and overflow event (reported at the top of each sheet). This also calculates the average observed data (N7 and S7 for drainage and overflow respectively), and the sum of the measured and modeled volumes for each event (N6 and P6 for drainage and S6 and U6 for overflow). The NSE and PBIAS for each event are summarized in the “Summary” worksheet.

“Make Graphs”: This sub-routine creates hydrographs of measured and modeled drainage and overflow for each event sheet. It can be run any time after “Create Sheets” but if it is used after “Statistics” then the total volumes will be reported in the legend of the graph. Graphs can be manually edited in the sheets if desired.

“Summary Stats”: This sub-routine calculates the cumulative NSE and PBIAS for all the events combined (as if they were lined end to end) and lists these values in the “Summary”. Additional statistics (r, R^2, MAE, MSE, RMSE, RSR, d, d_1, and E_1) were also calculated for the entire simulation and reported in the “Summary” worksheet.

“Validation: Odd Months” and “Calibration: Even Months”: These two sub-routines separate the cumulative NSE and PBIAS statistics into calibration and validation periods by separating events into even and odd months. These statistics are printed in the “Summary” worksheet.

“Hydrograph Summary”: This sub-routine calculates the peak flow, time to peak and duration for each drainage and overflow event and reports them in the “Hydrograph Summary” worksheet. Unit conversions are also built into the “Hydrograph Summary” worksheet.

Appendix B: Hydrographs of All Modeled Drainage and Overflow Events

Although examples of drainage and overflow hydrographs are given in the preceding work, it was not possible to include modeled hydrographs from all events. However, drainage and overflow hydrographs from all events are included here to show how DRAINMOD-Urban responded to different sized events as described in Table B.1. The NSE from each event for each of the categories below are shown in Table B.2 and B.3. The event hydrographs for drainage and overflow are included for the following categories: DRAINMOD-Urban uncalibrated, DRAINMOD-Urban volume calibration, DRAINMOD-Urban hydrograph calibration, SWMM uncalibrated, SWMM volume calibration, SWMM hydrograph calibration. Because there was little response in hydrographs of Chapter 4 using pedotransfer functions, they are not included in this appendix.

Table B-1. Storm characteristics, inflow (calculated in SWMM), and measured drainage and overflow for each event.

Event #	Storm Event Date	Rainfall (mm)	Average Intensity (in/hr)	Peak 5-min Intensity (in/hr)	Antecedent Dry Period (days)	Rainfall Duration (hrs)	Inflow (m^3)	Drainage (m^3)	Overflow (m^3)
1	6/18-19/2014	42.9	3.0	97.5	0.6	14.2	133.9	56.5	0.0
2	6/24-25/2014	97.0	4.9	152.4	0.6	18.1	297.0	195	51.8
3	7/7/2014	17.3	7.8	39.6	0.4	1.3	50.7	4.5	0.0
4	7/8/2014	45.0	12.9	109.7	0.5	3.5	152.4	84.7	34.0
5	7/9/2014	5.1	1.2	51.8	0.5	4.1	15.0	4.2	0.0
6	7/27-28/2014	86.1	3.8	79.2	0.7	18.4	222.1	114	40.1
7	8/12-13/2014	46.2	2.2	48.8	0.6	14.5	97.9	50.2	0.0
8	8/19-20/2014	28.2	2.6	39.6	2.6	10.8	83.0	14.8	0.0
9	9/5-6/2014	42.4	11.9	97.5	3.3	3.6	129.2	62.7	0.0
10	9/10-11/2014	48.3	3.7	64.0	4.6	13.0	150.0	64.6	5.6
11	10/3-4/2014	20.8	1.2	36.6	3.0	17.7	61.1	6.4	0.0
12	10/15-16/2014	39.6	5.2	36.6	0.7	4.9	77.9	35.8	0.0
	TOTAL:	**519**					**1470**	**693**	**132**

Table B-2. Drainage and overflow hydrograph performance in NSE and PBIAS under uncalibrated, volume-calibrated, and hydrograph-calibrated scenarios in DRAINMOD-Urban as compared to measured hydrographs.

	DRAINMOD-Urban: Uncalibrated				DRAINMOD-Urban: Volume Calibration				DRAINMOD-Urban: Hydrograph Calibration			
	Drainage		Overflow		Drainage		Overflow		Drainage		Overflow	
Event #	NSE	PBIAS	NSE	PBIAS	NSE	PBIAS	NSE	PBIAS	NSE	PBIAS	NSE	PBIAS
1	0.25	-18.0	-	-	0.23	-15.0	-	-	0.40	-29.2	-	-
2	0.21	58.6	-1.19	-94.2	0.22	50.5	-1.13	-109	0.34	42.6	-0.10	-42.2
3	-3.69	-292	-	-	-1.74	-138	-	-	-1.75	-82.6	-	-
4	0.39	0.16	-0.67	-37.7	0.46	16.2	-0.64	-32.8	0.65	4.9	0.74	20.1
5	-0.05	-67.6	-	-	-	-	-	-	-	-	-	-
6	0.55	20.2	-3.67	-58.6	0.37	32.8	-4.37	-70.8	0.80	5.4	-1.59	-14.8
7	0.09	-43.3	-	-	-0.09	-7.7	-	-	0.58	-5.8	-	-
8	-1.67	-81.9	-	-	-0.77	-158	-	-	-0.97	-131.2	-	-
9	0.27	-35.2	-	-	0.13	-4.8	-	-	0.39	-29.6	-	-
10	0.39	-42.9	-11.3	-194	0.34	52.0	-12.4	-539	0.62	28.0	-0.59	-59.7
11	-2.74	-411	-	-	-1.02	-246	-	-	-0.82	-180.9	-	-
12	-0.09	-35.0	-	-	0.56	-20.7	-	-	0.68	-8.0	-	-
Cumulative	**0.39**	**-1.6**	**-1.6**	**-73**	**0.31**	**17**	**-1.8**	**-97**	**0.60**	**5.2**	**-0.10**	**-18**

Table B-3. Drainage and overflow hydrograph performance in NSE and PBIAS under uncalibrated, volume-calibrated, and hydrograph-calibrated scenarios in SWMM as compared to measured hydrographs.

	SWMM: Uncalibrated				SWMM: Volume Calibration				SWMM: Hydrograph Calibration			
	Drainage		Overflow		Drainage		Overflow		Drainage		Overflow	
Event #	NSE	PBIAS	NSE	PBIAS	NSE	PBIAS	NSE	PBIAS	NSE	PBIAS	NSE	PBIAS
1	0.17	-31.6	-	-	-0.03	-11.8	-	-	-0.01	-58.6	-	-
2	0.50	2.5	0.57	9.7	0.51	18.6	0.16	-22.6	0.65	-5.2	0.66	12.2
3	-	-	-	-	-	-	-	-	-	-	-	-
4	-0.02	-21.3	0.68	42.7	0.11	6.7	0.58	25.4	0.40	-38.5	0.67	43.3
5	0.71	20.8	-	-	-	-	-	-	-0.10	8.3	-	-
6	0.27	-15.4	0.01	18.2	0.48	4.2	-1.08	-6.3	0.46	-30.1	0.11	24.5
7	0.21	-8.9	-	-	0.46	6.3	-	-	0.45	-37.7	-	-
8	-3.32	-84.1	-	-	-0.09	51.4	-	-	-1.49	-184	-	-
9	-0.49	-24.4	-	-	-0.46	-27.4	-	-	0.07	-48.3	-	-
10	-0.54	-42.8	-0.15	73.3	0.26	-27.8	-0.14	15.1	0.04	-64.8	-0.45	88.2
11	0.19	33.1	-	-	0.04	52.7	-	-	-0.42	-172	-	-
12	-2.52	-36.4	-	-	-0.24	13.6	-	-	-0.90	-59.1	-	-
Cumulative	**0.25**	**-17**	**0.52**	**24**	**0.41**	**3.5**	**0.11**	**-3.6**	**0.42**	**-38**	**0.58**	**27**

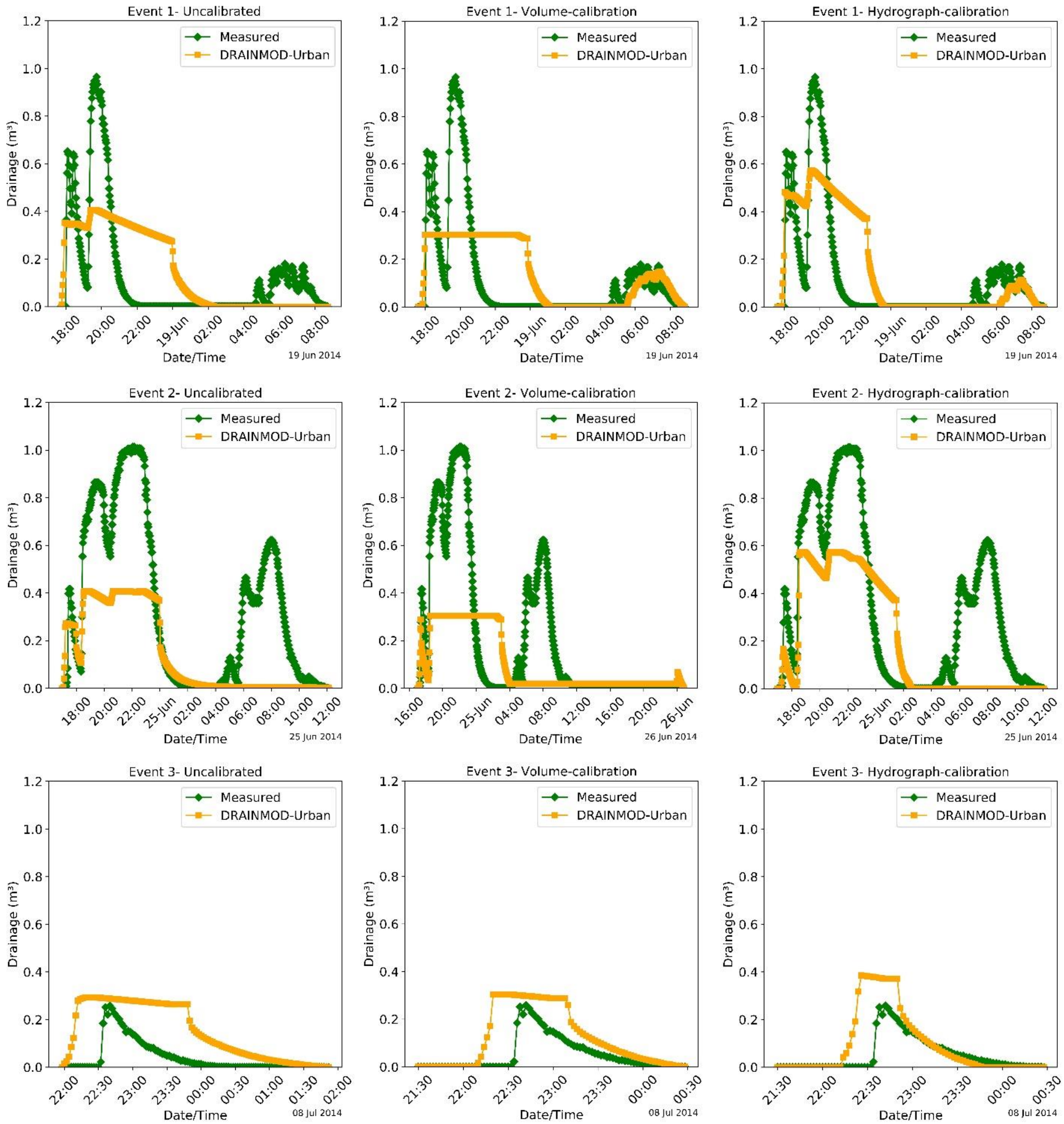


Figure B-1. Drainage hydrographs for events 1-3 under uncalibrated, volume-calibrated, and hydrograph-calibrated scenarios in DRAINMOD-Urban as compared to measured hydrographs.

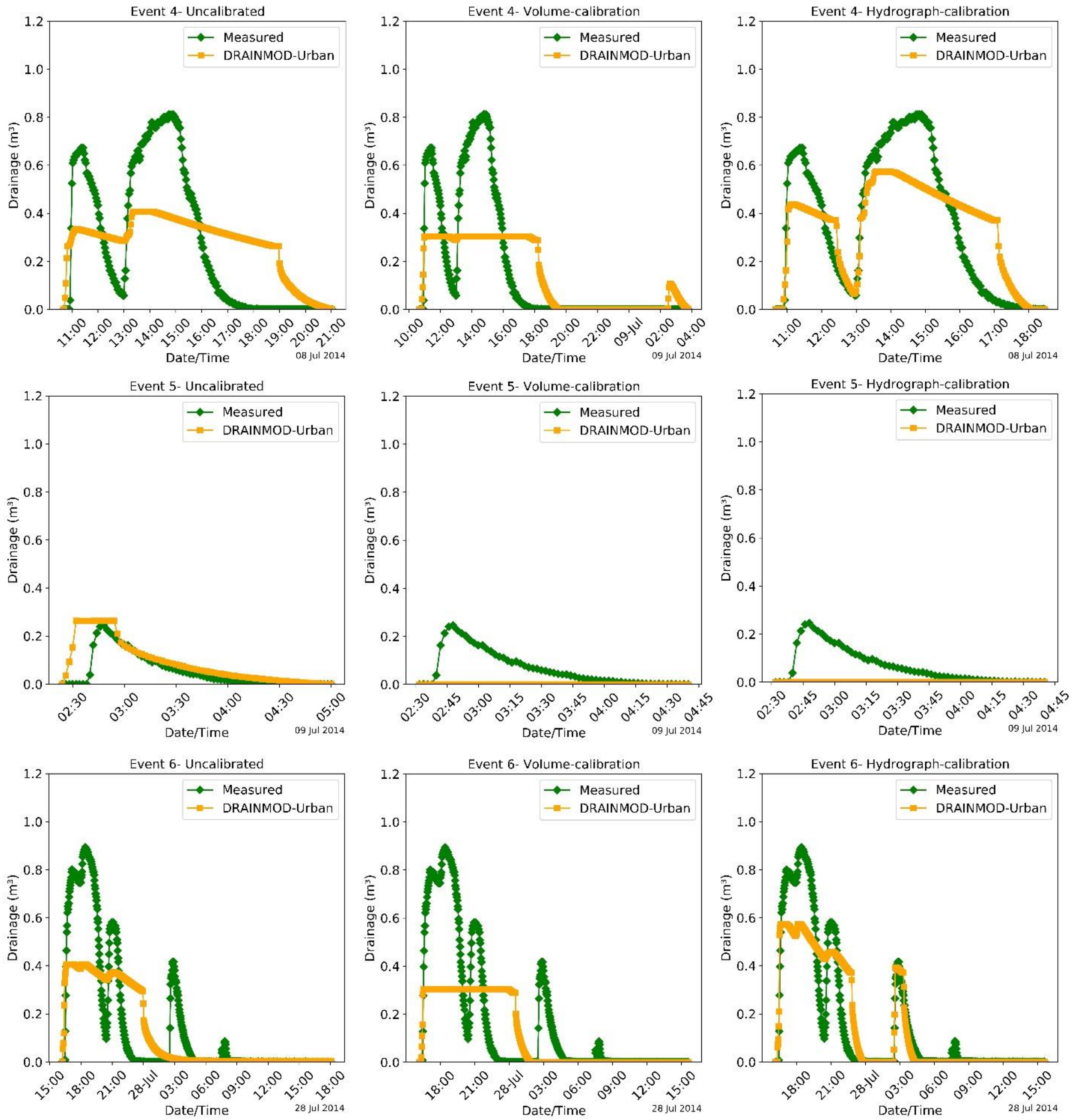


Figure B-2. Drainage hydrographs for events 4-6 under uncalibrated, volume-calibrated, and hydrograph-calibrated scenarios in DRAINMOD-Urban as compared to measured hydrographs.

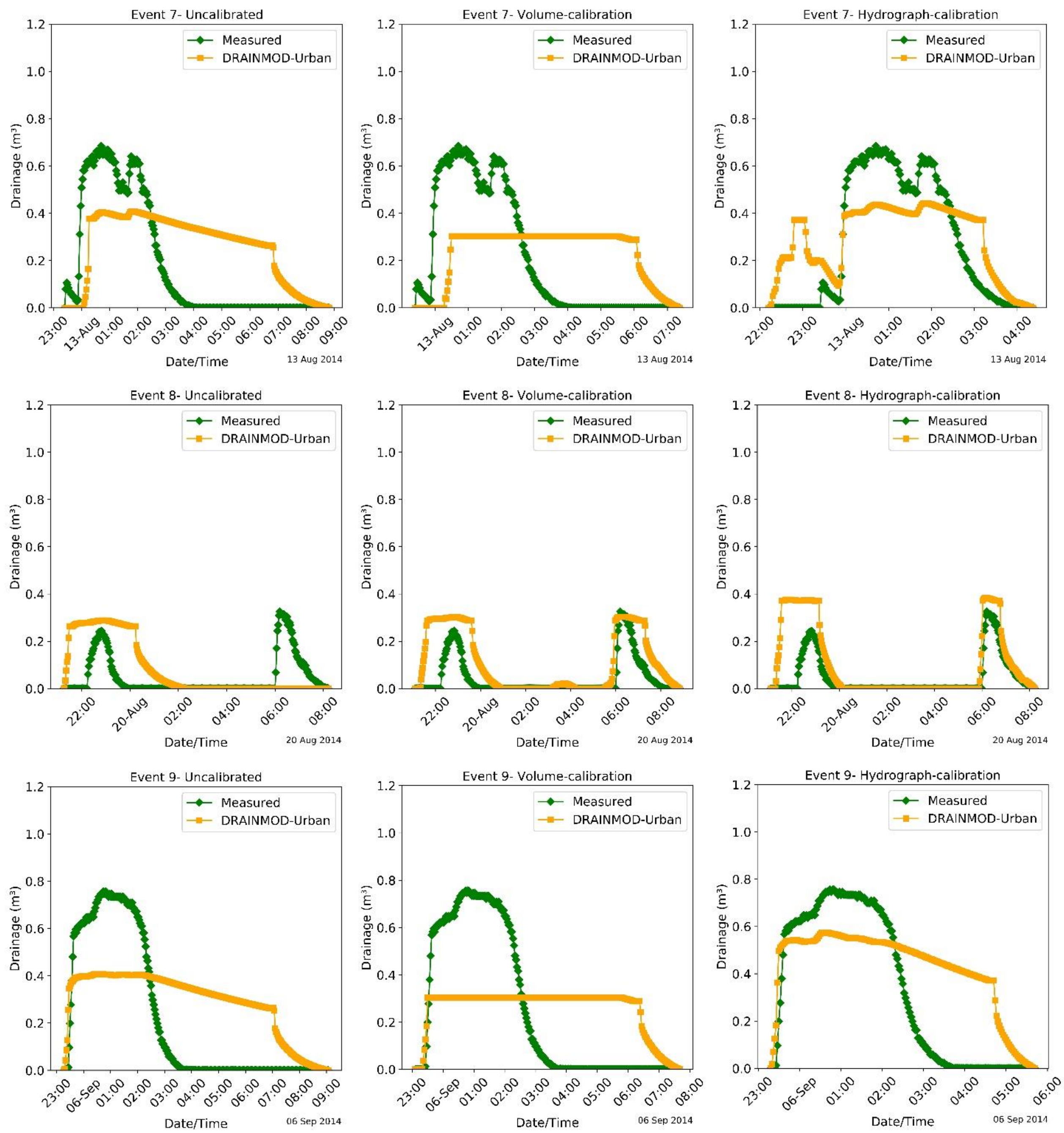


Figure B-3. Drainage hydrographs for events 7-9 under uncalibrated, volume-calibrated, and hydrograph-calibrated scenarios in DRAINMOD-Urban as compared to measured hydrographs.

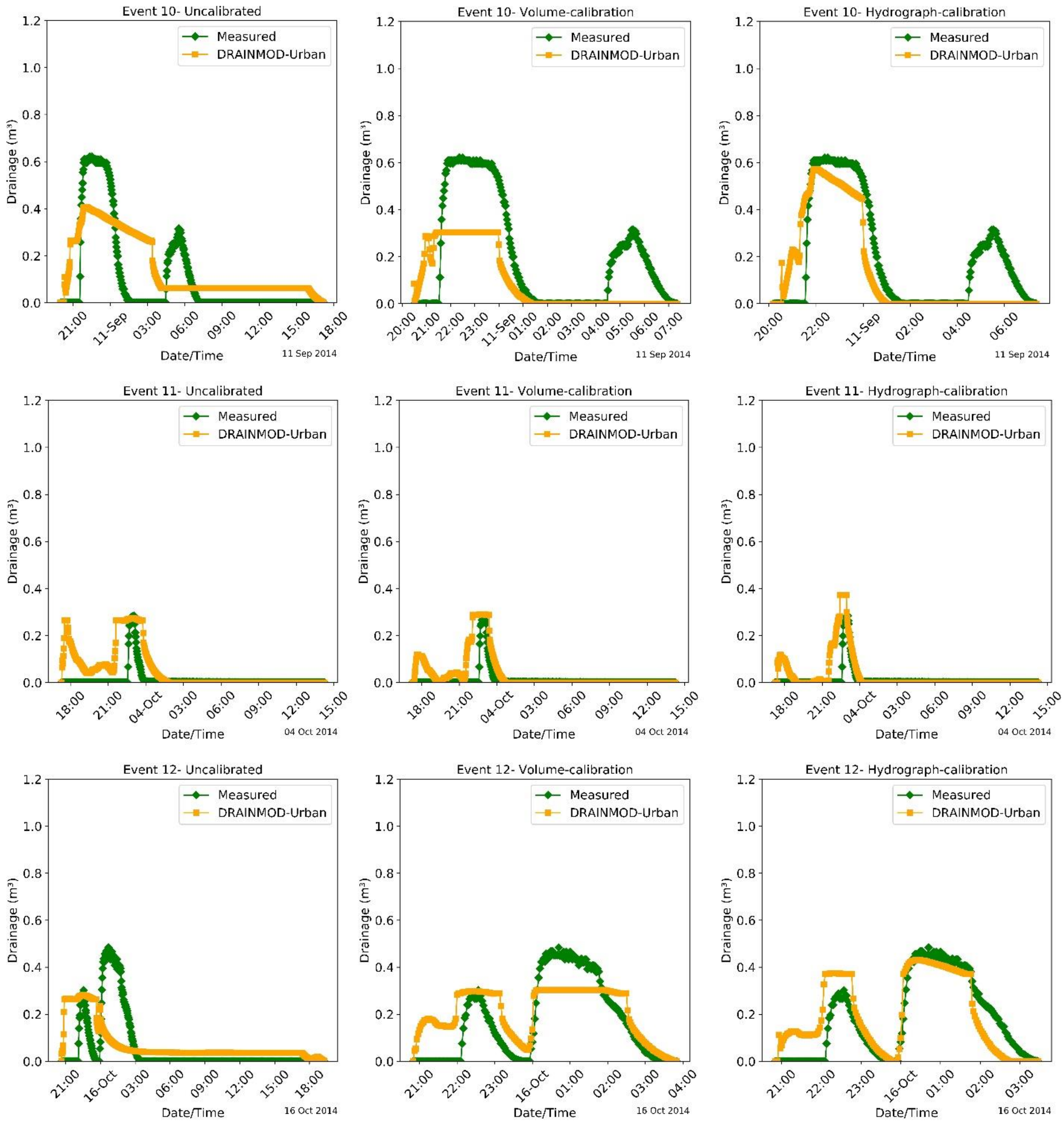


Figure B-4. Drainage hydrographs for events 10-12 under uncalibrated, volume-calibrated, and hydrograph-calibrated scenarios in DRAINMOD-Urban as compared to measured hydrographs.

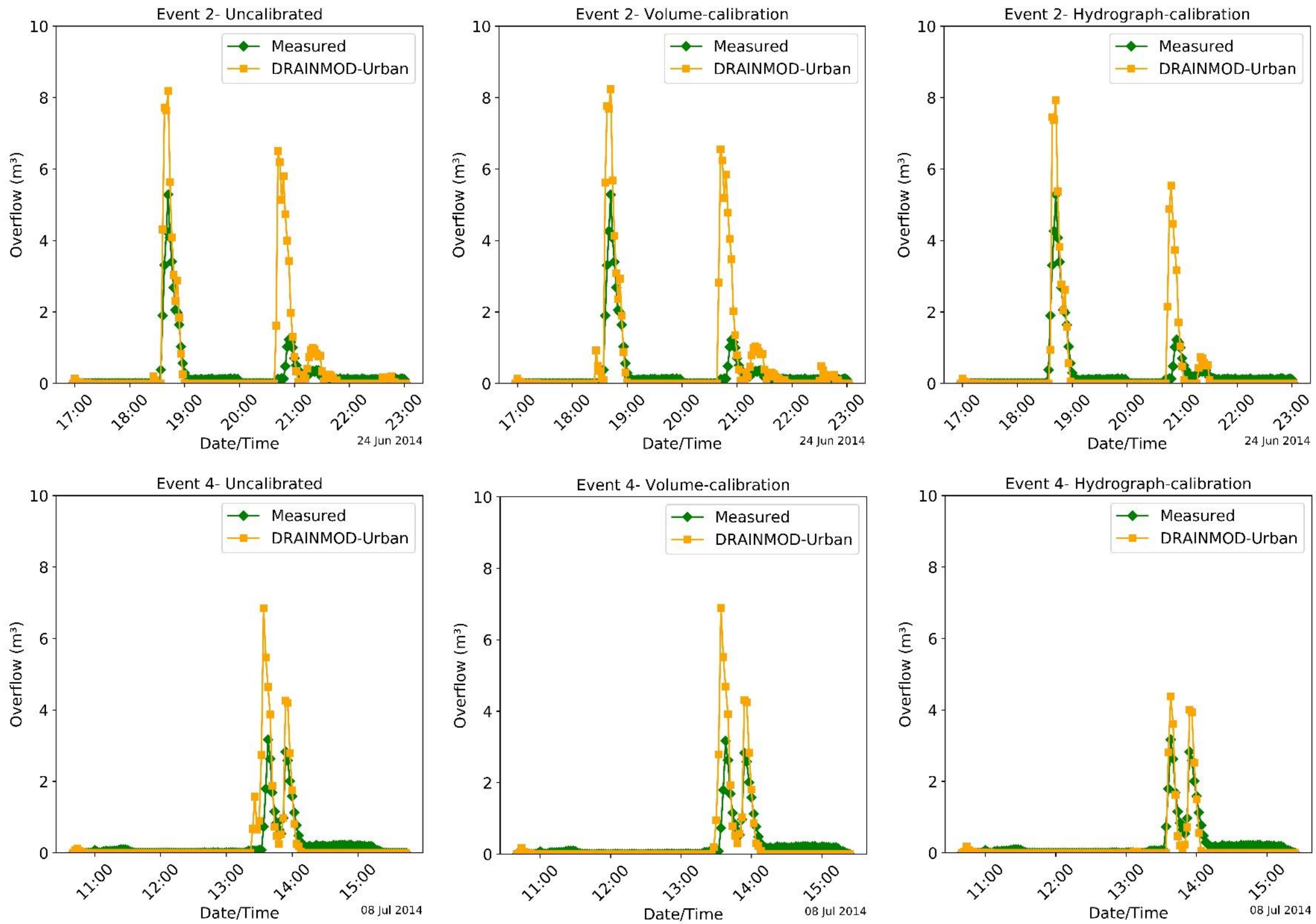


Figure B-5. Overflow hydrographs for events 2 and 4 under uncalibrated, volume-calibrated, and hydrograph-calibrated scenarios in DRAINMOD-Urban as compared to measured hydrographs.

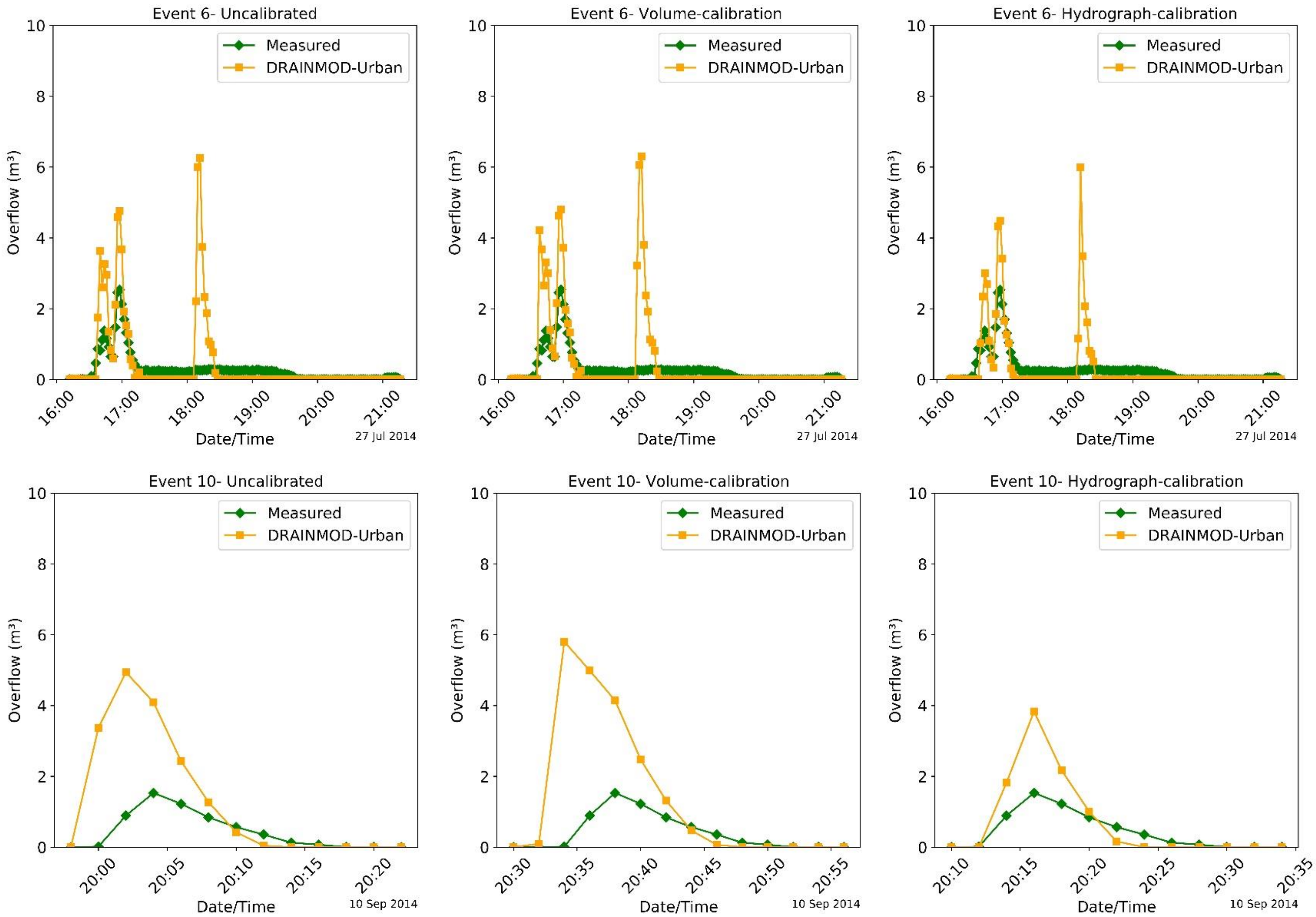


Figure B-6. Overflow hydrographs for events 6 and 10 under uncalibrated, volume-calibrated, and hydrograph-calibrated scenarios in DRAINMOD-Urban as compared to measured hydrographs.

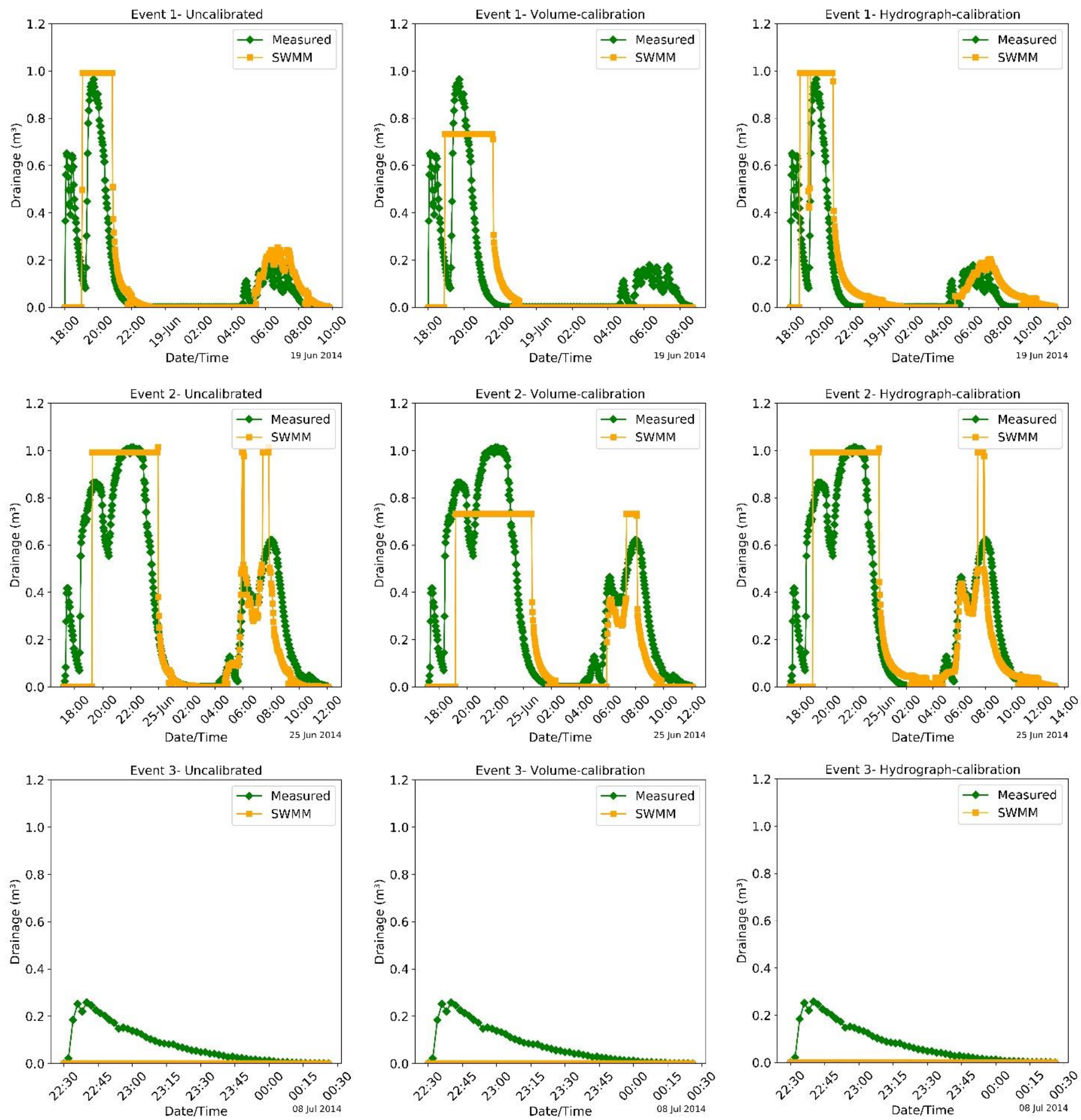


Figure B-7. Drainage hydrographs for events 1-3 under uncalibrated, volume-calibrated, and hydrograph-calibrated scenarios in SWMM as compared to measured hydrographs.

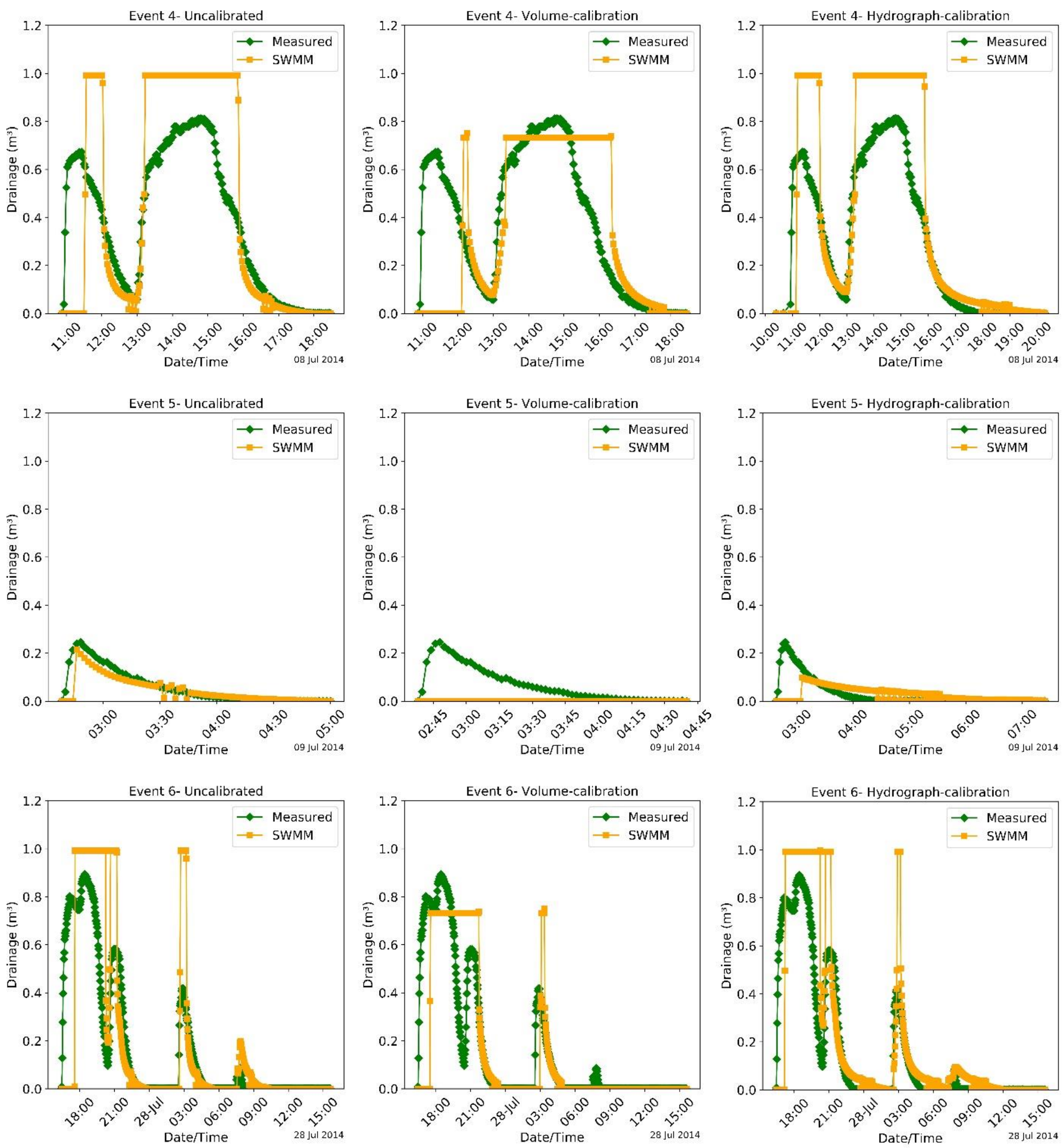


Figure B-8. Drainage hydrographs for events 4-6 under uncalibrated, volume-calibrated, and hydrograph-calibrated scenarios in SWMM as compared to measured hydrographs.

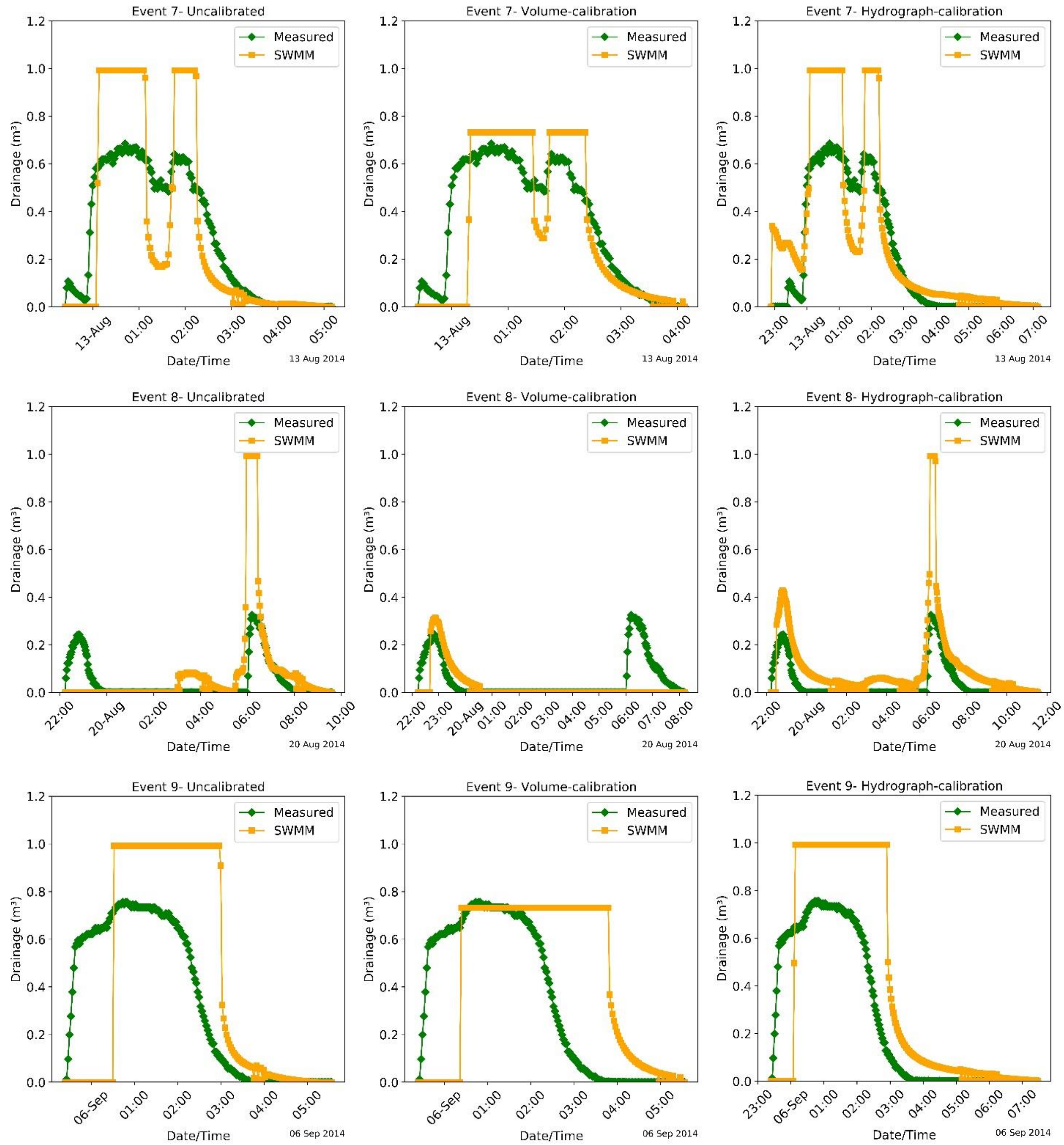


Figure B-9. Drainage hydrographs for events 7-9 under uncalibrated, volume-calibrated, and hydrograph-calibrated scenarios in SWMM as compared to measured hydrographs.

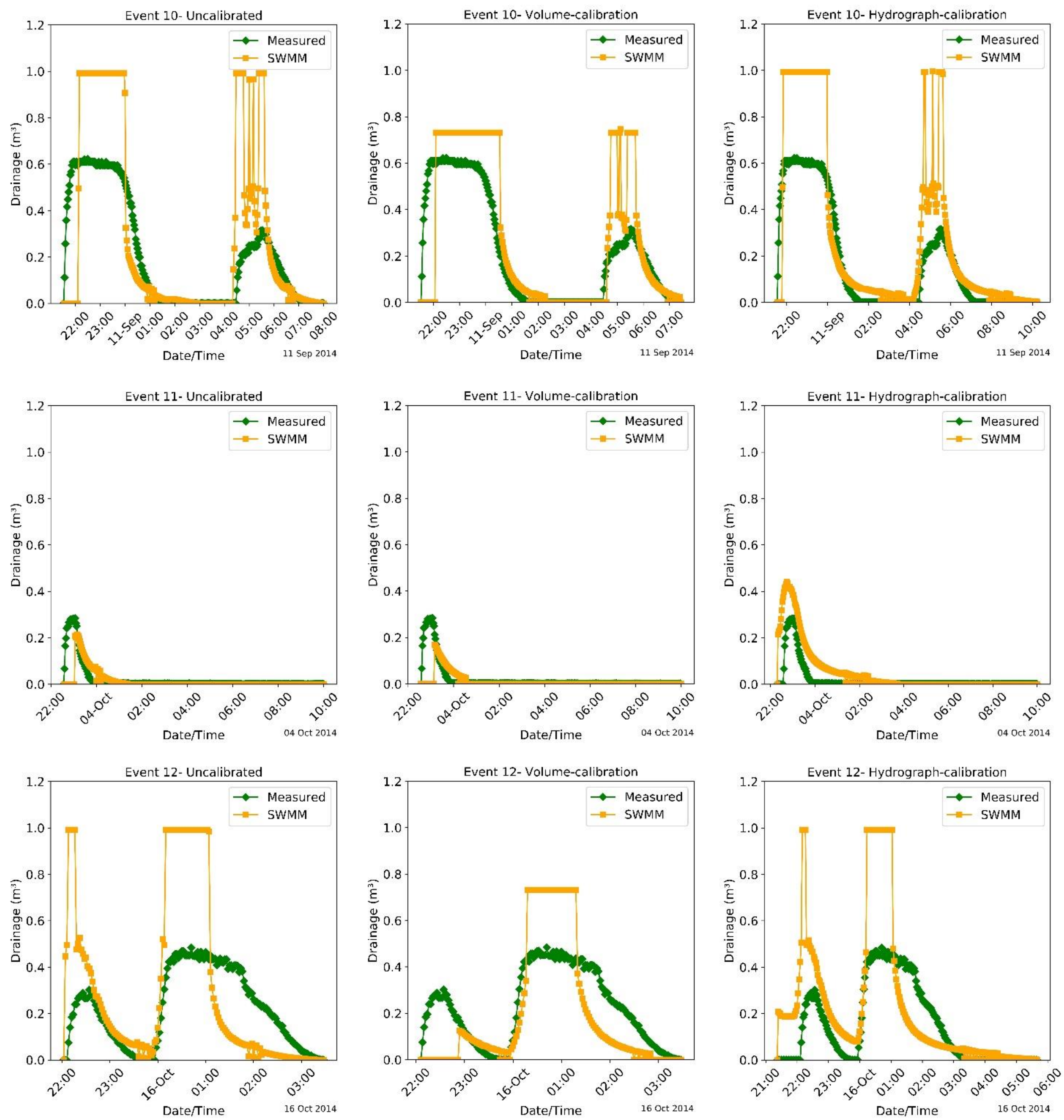


Figure B-10. Drainage hydrographs for events 10-12 under uncalibrated, volume-calibrated, and hydrograph-calibrated scenarios in SWMM as compared to measured hydrographs.

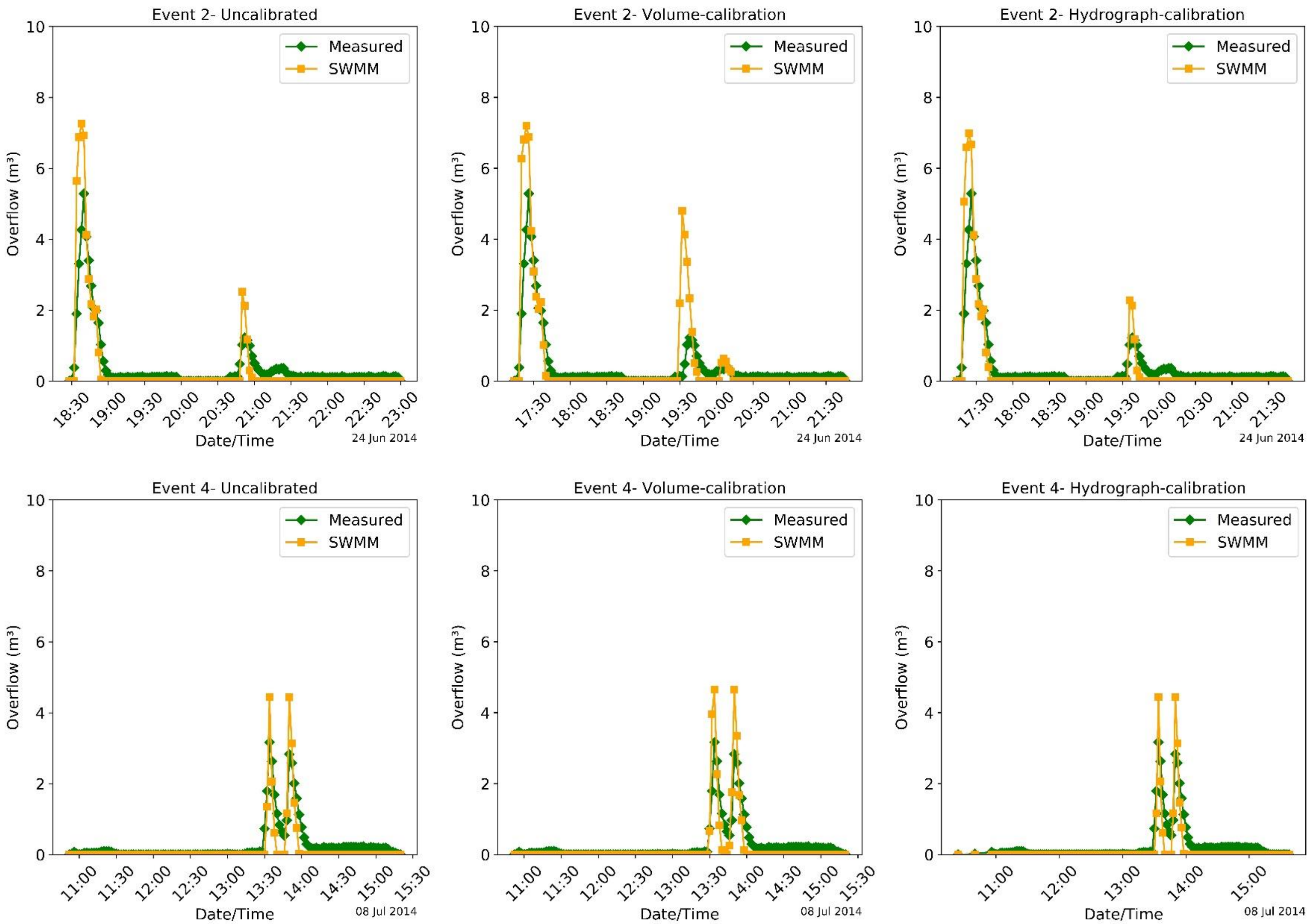


Figure B-11. Overflow hydrographs for events 2 and 4 under uncalibrated, volume-calibrated, and hydrograph-calibrated scenarios in SWMM as compared to measured hydrographs.

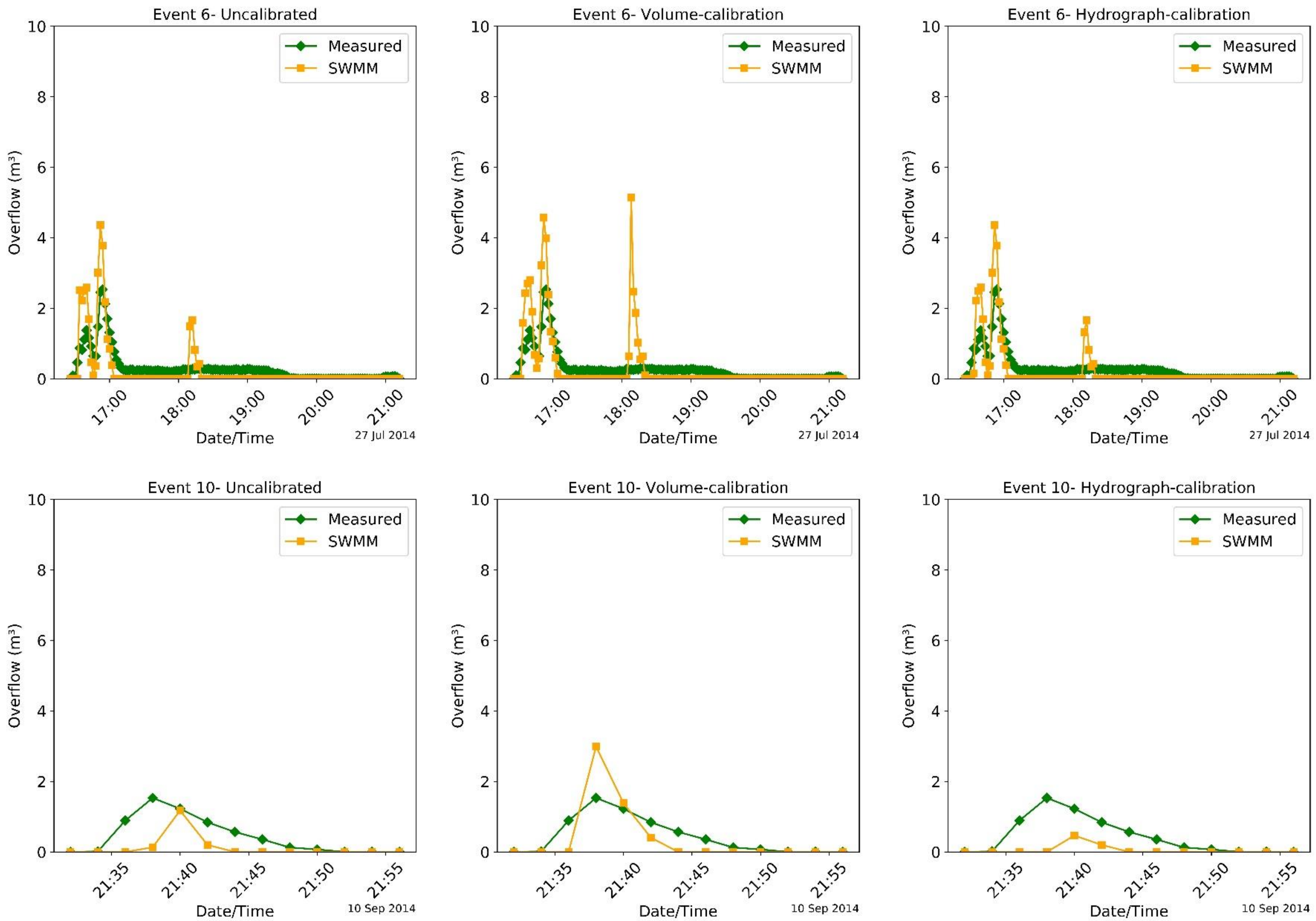


Figure B-12. Overflow hydrographs for events 6 and 10 under uncalibrated, volume-calibrated, and hydrograph-calibrated scenarios in SWMM as compared to measured hydrographs.

Appendix C: Measured Soil Water Characteristic Curve for Ursuline College Bioretention Cell Media

Table C-1. SWCC from each individual soil sample taken at the UC bioretention cell and an average SWCC.

Pressure head		Volumetric Water Content (m^3/m^3)			
(m)	(kPa)	UC_avg	UC1	UC2	UC3
0	0	0.331	0.304	0.340	0.348
-0.04	-0.39	0.331	0.304	0.340	0.348
-0.1	-0.98	0.331	0.304	0.340	0.348
-0.3	-2.94	0.258	0.253	0.251	0.269
-0.6	-5.88	0.217	0.225	0.213	0.215
-1	-9.81	0.201	0.209	0.200	0.194
-2	-19.6	0.19	0.193	0.194	0.183
-3	-29.4	0.179	0.177	0.184	0.176
-4	-39.2	0.174	0.171	0.181	0.170
-6	-58.8	0.15			

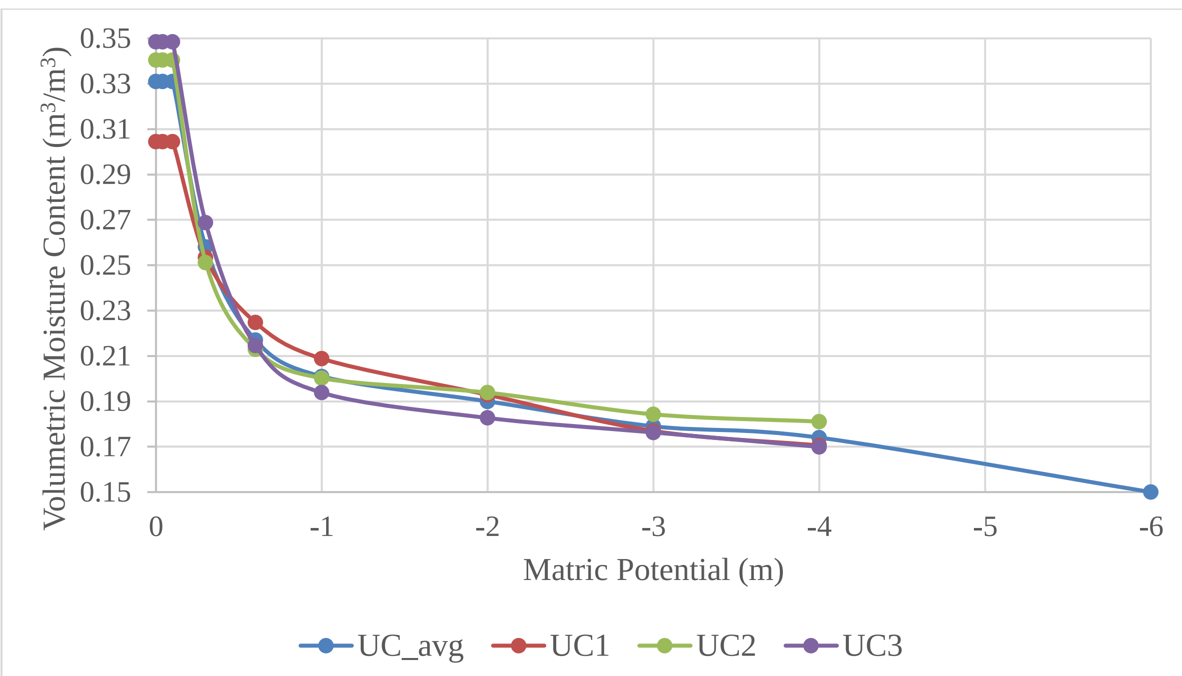


Figure C-1. SWCC from each individual soil sample taken at the UC bioretention cell and an average SWCC.

VITA

Whitney Lisenbee received her B.S. and M.S. degrees in Biosystems and Agricultural Engineering from Oklahoma State University. Her master's thesis is titled: Comparison of Water Quality and Quantity in Eastern Redcedar-Encroached Woodland and Native Tallgrass Prairie Watersheds: A Monitoring and Modeling Study. This research explored stream hydrology and erosion processes in native prairie and agricultural watersheds in Oklahoma and modeled surface runoff and sediment concentrations in WEPP.

Whitney served as a Graduate Research Assistant, and recipient of the Chancellor's Fellowship, while obtaining her Ph.D. in Civil and Environmental Engineering from University of Tennessee-Knoxville. Her dissertation research was primarily focused on improving modeling of bioretention cells for stormwater management and watershed restoration. Her research concentration was in water resources and hydrology with interests including soil erosion, streambank stabilization, land use changes, urban hydrology, water quantity/quality, stormwater mitigation, and low impact development. She is also interested in conflicts between urban and agricultural water quantity and quality.

Whitney was designated a PEO Scholar in 2018, a prestigious distinction as one of 100 women in PhD programs dedicated to making significant scientific contributions and supporting other women in their field. She a member of the American Society of Agricultural and Biological Engineers (ASABE), the American Society of Civil Engineers-Environmental & Water Resources Institute (ASCE-EWRI), American Ecological Engineering Society (AEES), and the American Society of Engineering Education (ASEE).